HIGH-TEMPERATURE LUBRICANTS FOR MINIMUM-COOLED DIESEL ENGINES

INTERIM REPORT
AFLRL No. 171

By

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Under Contract to

U.S. Army Belvoir Research and Development Center
Materials, Fuels, and Lubricants Laboratory
Fort Belvoir, Virginia

Contract No. DAAK70-82-C-0001

November 1983

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFLRL No. 171

2. GOVT ACCESSION NO: AD-A142

3. RECIPIENT'S CATALOG NUMBER: 426

4. TITLE (and Subtitle): HIGH-TEMPERATURE LUBRICANTS FOR MINIMUM-COOLED DIESEL ENGINES

5. TYPE OF REPORT & PERIOD COVERED: INTERIM REPORT, Oct 1980 to November 1983

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): E.A. Frame

8. CONTRACT OR GRANT NUMBER(s): DAAK70-80-C-0001, DAAK70-82-C-0001

9. PERFORMING ORGANIZATION NAME AND ADDRESSES: U.S. Army Fuels & Lubricants Research Laboratory, 6220 Culebra Road, San Antonio, TX 78251

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 1L762733AH20VLL;WUB06

11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Belvoir Research and Development Center, Fuels and Lubricants Division, Fort Belvoir, VA 22060

12. REPORT DATE: November 1983

13. NUMBER OF PAGES: 67

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work was jointly funded by U.S. Army Tank Automotive Command, DRSTA-RG, Warren MI, 48090, and U.S. Army Belvoir Research and Development Center, STRBE-VF, Ft. Belvoir, VA 22060.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lubricant	Diesel Engine Oil
Diesel Engine	High-Temperature Oil
Adiabatic Engine	Minimum-Cooled Engine

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Lubricant performance at high temperatures was defined using an uncooled single-cylinder diesel engine operated at conditions which simulate a minimum-cooled/adiabatic diesel engine. The following lubricant-related problems were observed:

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20. ABSTRACT (Cont'd)

- Lubricant oxidation--oil too thick to pump; corrosive products formed and bearings attacked.
- Lubricant volatility--high oil consumption, oil thickening.
- Engine deposits--ring sticking.

A variety of high-temperature candidate lubricants was evaluated in the uncooled single-cylinder diesel engine. Two promising lubricants have been identified:

- AL-11878 which contains diphenylether basestock material and a calcium detergent-dispersant additive system.
- AL-11848 which contains diester and PAO basestocks and a barium detergent-dispersant additive system; AL-11848 does not contain zinc.

While these two oils had the best overall high-temperature performance of the candidates tested, they were still deficient in oxidation stability/oil thickening properties.

High-pressure differential scanning calorimetry (HPDSC) and FTM5308 were investigated for use as high-temperature lubricant bench screening methods. Neither method was completely satisfactory, and additional development of a bench oxidation screening technique is needed.

FOREWORD

The work reported herein was conducted at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL), Southwest Research Institute, San Antonio, TX, under Contract Nos. DAAK70-80-C-0001 and DAAK70-82-C-0001 and covers the period October 1980 - November 1983. The work was jointly funded by the U.S. Army Belvoir Research and Development Center, formerly MERADCOM, Ft. Belvoir, VA, and the U.S. Army Tank Automotive Command, Warren, MI. Contracting officer's representative was Mr. F.W. Schaekel, Fuels and Lubricant Division/STRBE-VF (formerly DRDME-GL), and the technical monitors were Mr. T.C. Bowen, Fuels and Lubricants Division/STRBE-VF, Belvoir R&D Center, and Dr. Walter Bryzik, Propulsion Systems Division/DRSTA-RG, TACOM.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions of the AFLRL chemical and engine laboratory staff, especially Mr. J.T. Ford. The assistance of the AFLRL editorial staff (Ms. L. Pierce and Mr. J. Pryor) in preparing this report was greatly appreciated.

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I. INTRODUCTION

The adiabatic diesel engine and other high-temperature, high-output engines are possible future powerplants for U.S. Army equipment. The adiabatic diesel engine concept involves insulation of the diesel combustion chamber to retain thermal energy within the engine. Engine cooling and exhaust are the primary areas where thermal energy escapes the diesel engine. The efficiency of a diesel engine can be increased by utilizing turbomachinery to recover thermal energy normally lost to cooling and exhaust. The adiabatic diesel engine can offer the military the advantages of improved fuel economy and reduced engine weight/volume requirements for a given desired power output.(1-6)* Also, it can decrease maintenance requirements and vulnerability of a military vehicle by eliminating the need for a liquid cooling system.

When thermal energy is retained within a diesel engine, the engine oil temperature environment increases, which results in thermal stressing of the engine lubricant. Conventional diesel engines have cylinder liner temperatures at top ring reversal (TRR) of approximately 204°C (400°F). Adiabatic diesel engines can have cylinder liner temperatures at TRR of 370°C to 760°C (700°F to 1400°F).(6,7) At these high TRR temperatures, lubricant volatilization which results in high oil consumption and oil oxidation are potential problem areas.

The objective of this Army research project was to develop lubrication requirements for new/advanced engine systems such as the adiabatic diesel engine. The approach involved first obtaining and characterizing high-temperature lubricant (HTL) candidates. Next, the candidate lubricants were screened using a simulated adiabatic single-cylinder diesel engine. From the engine screening tests, HTL requirements were determined, and high-temperature lubricant candidates were evaluated. Additionally, bench-scale lubricant screening tests were investigated for use in predicting critical lubricant properties such as oxidation resistance. Several lubricants were

*Underscored numbers in parentheses refer to the references at the end of this report.

identified which have potential for use as engine oils in minimum-cooled diesel engines.

II. DEVELOPMENT OF AN ENGINE TEST PROCEDURE FOR SCREENING HIGH-TEMPERATURE LUBRICANTS

A. Engine Description

An investigation was initiated to determine the feasibility of operating the single-cylinder CLR-diesel engine at high cylinder wall temperatures which simulate the temperature environment of the adiabatic diesel engine. A description of the CLR-D engine is presented in Table 1 with the engine/dynamometer installation shown in Figures 1 and 2. The CLR-D engine was chosen for use because it is a small single-cylinder engine which reduces the quantity of fuel and experimental lubricant required for operation. Additionally, parts are readily available for this engine, and the Army Fuels and Lubricants Research Laboratory (AFLRL) has had extensive experience with the CLR engine.

TABLE 1. COORDINATED LUBRICANTS RESEARCH DIESEL ENGINE (CLR-D) CHARACTERISTICS

Displacement	42.5 $in.^3$	
Bore and Stroke	3.80 in. X 3.75 in.	
Compression Ratio	14.3:1	
Piston	Aluminum, 3-Ring	
Piston Rings	Top Compression:	rectangular, barrel-faced chrome
	Second Compression:	rectangular, square-faced cast iron
	Oil Control:	two chrome rails and expander
Cylinder	Replaceable Cast Iron Sleeve	
Connecting Rod Bearings	Copper-lead	
Oil Capacity	1 Quart (no filter)	

Initially, ten iron-constantan thermocouples were installed in the cylinder liner area to monitor the temperature of the liner surface exposed to the oil lubricating film. The cylinder liner was drilled and the constantan

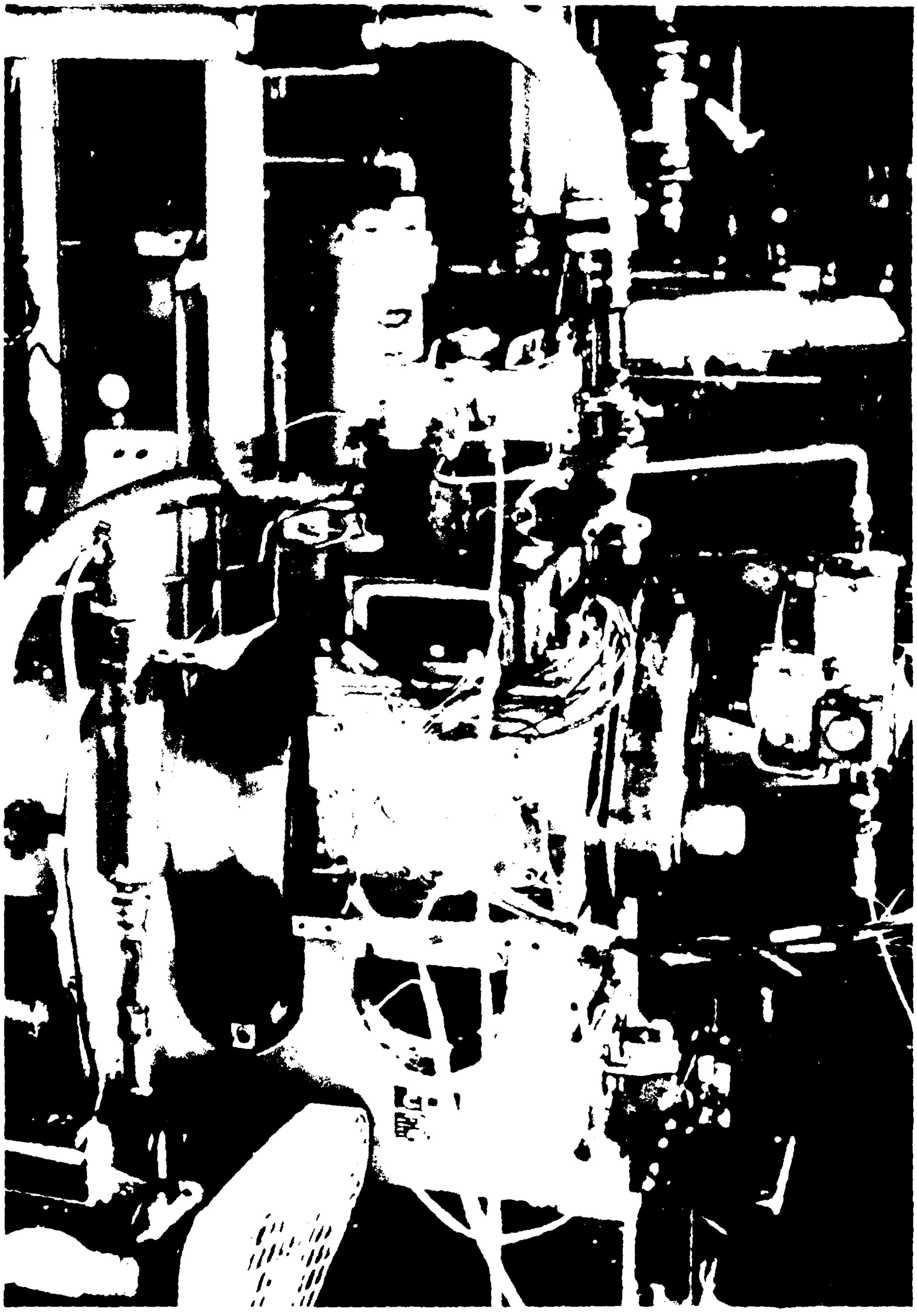


FIGURE 1. UNCOOLED CLR--DIESEL

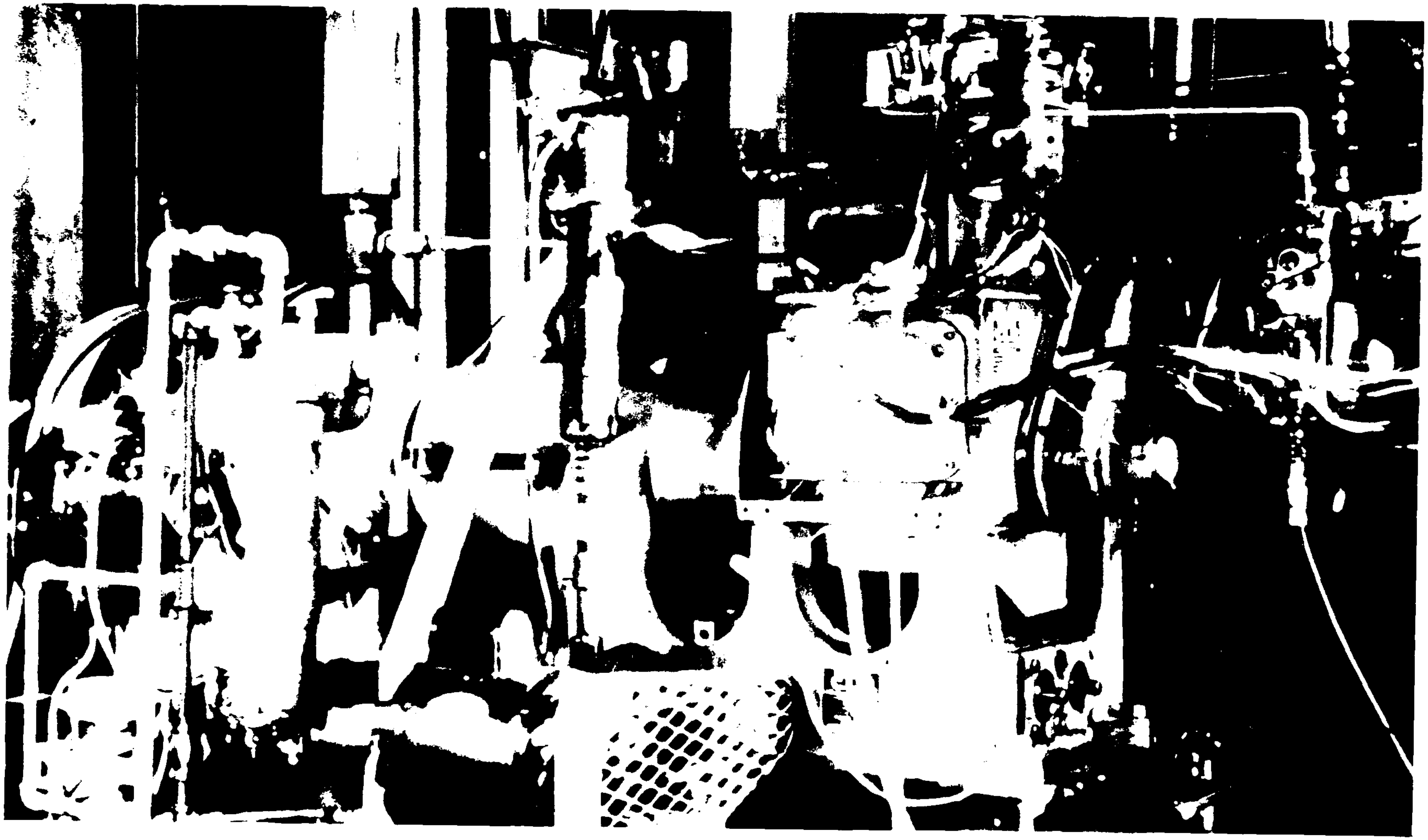
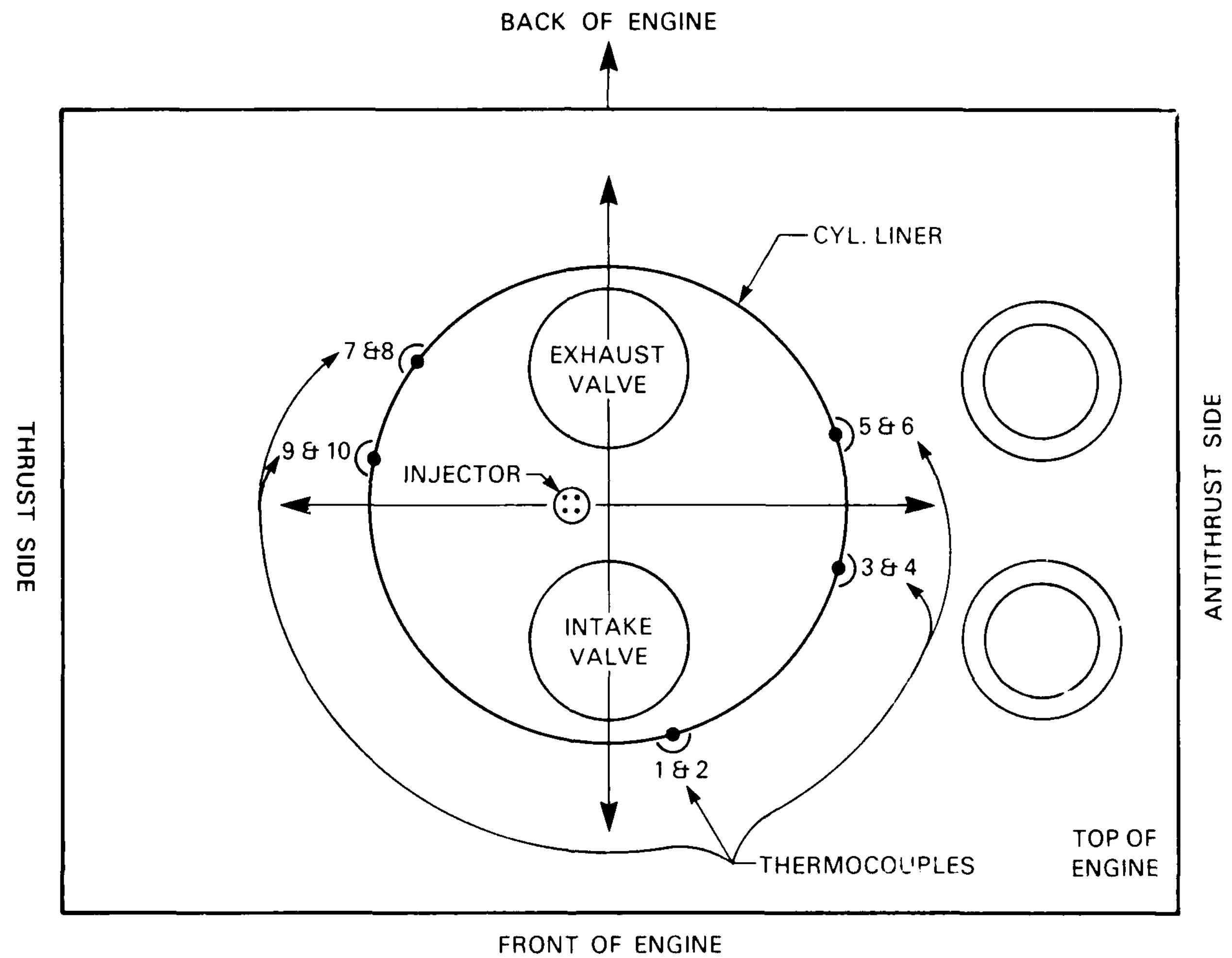


FIGURE 2. UNCOOLED CLR--DIESEL (SIDE VIEW)

wire of each thermocouple was welded flush to the liner surface.(8) The locations of the thermocouples are shown in Figure 3. The thermocouple wires exited the engine through a standpipe in the jug. Calibration of the thermocouples was checked by placing the liner with thermocouples installed in an oven with temperatures up to 371°C (700°F) and observing their accuracy against the known oven temperature. Generally, the thermocouples read within approximately 10°F of the known temperature; thus, no correction factor was applied.



THERMOCOUPLE POSITION—INCHES DOWN LINER FROM TOP

0.5625 IN. #1, 3, 5
1.1875 IN. #7, 9
1.5625 IN. #4
2.4375 IN. #2, 6
2.8125 IN. #8, 10

FIGURE 3. CLR--DIESEL THERMOCOUPLE POSITIONS

B. Test Fuel

The reference No. 2 diesel fuel used in this program was a nominal VV-F-800C No. 2 diesel fuel conforming to the requirements established by Federal Test Method 791B, Method 354. This test fuel is a straight-run, mid-range natural sulfur fuel which is manufactured under closely controlled refinery operation to minimize batch-to-batch compositional and physical property deviations. The analysis of the test fuel is presented in Table 2.

TABLE 2. TEST FUEL ANALYSIS

Property	ASTM Method No.	Reference No. 2 DF Test Fuel	Specification[a]
Gravity, API°	D 287	34.5	Record
Viscosity, cSt, 38°C(100°F)	D 445	3.3	1.6-4.5
Flash Point, °C(°F)	D 93	85(185)	37.8(100) min
Cloud Point, °C(°F)	D 2500	-2.0(+28)	Record
Pour Point, °C(°F)	D 97	-12(+10)	-6.7(+20) max
Water and Sediment, vol%	D 1796	0.0	0.5 max
Carbon Residue, wt%	D 524	0.10	0.20 max
Sulfur, wt%	D 129	0.41	0.35 min
Acid No., mg KOH/g	D 664	0.0	Record
Aniline Point, °C(°F)	D 611	63(145)	Record
Copper Corrosion	D 130	1A	No. 2 max
Distillation, °C(°F)	D 86		
IBP		207(405)	Record
10%		241(465)	Record
50%		273(524)	260(500) min
90%		317(603)	316-338(600-640)
EP		348(658)	343-366(650-690)
Cetane No.	D 613	52	40-45
Net Heat of Combustion MJ/kg (Btu/lb)	D 240	42.13(18,130)	Record
Ash, wt%	D 482	0.006	0.01 max

a = Section 4.1 Method 354 FTM Std 791B

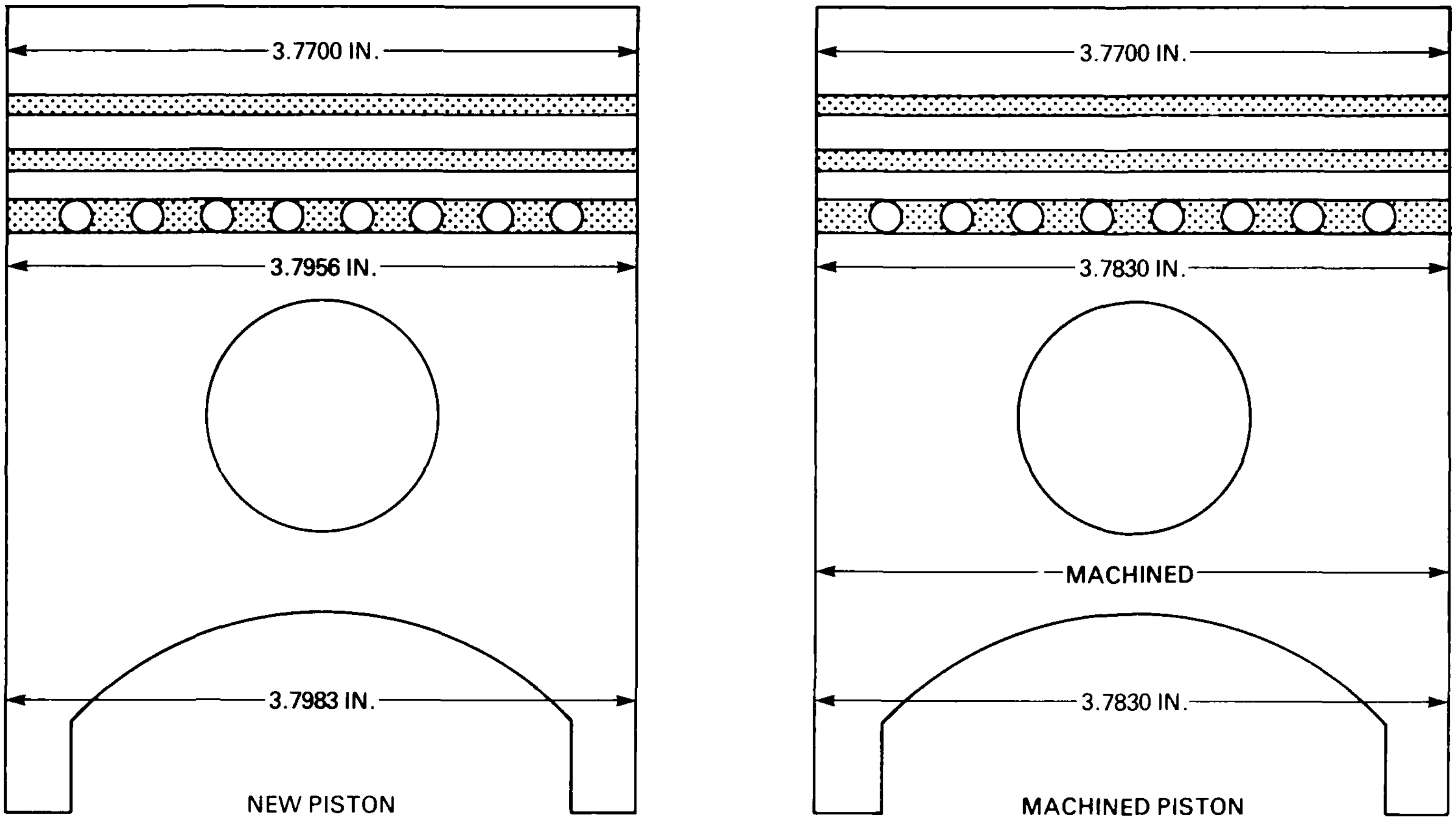
C. Engine Modifications for High-Temperature Operation

A series of CLR-D engine tests were conducted to determine the feasibility of operating this engine at a sufficiently high cylinder wall temperature to simulate the temperature environment of an adiabatic engine. Lubricant AL-7135, which had exhibited excellent high-temperature volatility proper-

ties, was used for this test series. A summary of these tests is presented in Table 3. At operating conditions of air/fuel ratio=30 and 1800 RPM, the maximum cylinder liner temperature observed was 184°C. The CLR-D liner and head had separate cooling systems which allowed the liner to be operated at high temperatures, while the head area was kept cooler to prevent head gasket damage. Operating conditions and liner cooling materials were varied to increase the liner temperature. First, heated vegetable oil was circulated through the liner jacket area, which raised the cylinder wall temperature to 227°C. In Test No. 3, the liquid coolant was removed and liner area was cooled with compressed air which allowed a wall temperature of 266°C, which was still well below the desired 370°C. To further increase wall temperature, Test No. 4 was run at 2500 RPM with a lower A/F ratio (more energy input) and with dead air cooling the liner area. This resulted in a wall temperature of 392°C; however, the piston stuck in the liner and the wrist pin was stuck in the piston boss. Next, the engine was modified to accommodate high-temperature operation. The piston was machined to increase piston/liner clearance as shown in Figure 4. Lubrication of the piston undercrown and wrist pin areas was increased. The top connecting rod bearing was grooved, and a hole was drilled in the center as shown in Figure 5. This allowed oil to flow to a 1/8-inch stainless steel tube which was inserted in the center of the connecting rod. This modification permitted oil to be fed to the piston undercrown and wrist pin (Figure 6). The ends of the wrist pin were plugged, and three grooves were cut around the wrist pin to allow oil flow as shown in Figure 7. Test No. 5 was run with these modifications, and a maximum liner temperature of 419°C was achieved; however, the piston again stuck in the liner, and the wrist pin was tight in the piston. All three piston rings were stuck due to lubricant coking. For Test No. 6, engine speed was reduced to 2000 RPM, the oil charge was increased from 0.95 to 2.3 L, the piston/liner clearance was increased slightly to 0.45 mm, and oil delivery to the piston undercrown was increased. A maximum liner temperature of 361°C was achieved, and the piston remained free in the liner. The wrist pin also remained free in the piston; however, once again, the rings were stuck. For Test No. 7, all Test No. 6 changes were retained, and ring side clearance was increased from 0.032 to 0.089 mm. This resulted

TABLE 3. HIGH-TEMPERATURE CLR-DIESEL TEST DEVELOPMENT

Test Number:	1	2	3	4	5	6	7
Lubricant:	AL-7135	AL-7135	AL-7135	AL-7135	AL-7135	AL-7135	AL-7135
Operating Conditions							
RPM	1800	1800	2500	2500	2000	2000	2000
Load, lb	20	19	20	18	16	20	17
Air/Fuel Ratio	30	29	30	25	22	21.4	22.5
Coolant Temp in Heat, °F(°C)	120-140(49.60)	170(77)	140(60)	170(77)	186(86)	126(52)	118(48)
Oil Temp (gallery), °F(°C)	230(110)	232(111)	235(113)	262(128)	364(194)	321(160)	335(168)
Max Observed Liner Temp, °F(°C)	364(184)	440(227)	510(266)	737(392)	787(419)	682(361)	650(343)
Engine Modifications							
Liner Area Coolant	100% Glycol	Heated Vegetable Oil	Air Flow	Dead Air	Dead Air	Dead Air	Dead Air
Piston/Liner Clearance, in.(mm)	0.0068(0.173)	0.0068(0.173)	0.0068(0.173)	0.0068(0.173)	0.015(0.38)	0.018(0.45)	0.018(0.45)
Ring Side Clearance, in.(mm)	0.0015(0.032)	0.0015(0.032)	0.0015(0.032)	0.0015(0.032)	0.015(0.032)	0.015(0.032)	0.0035(0.089)
Engine Rebuild	Yes	No	No	No	Yes	Yes	Yes
Machined Piston to Incr. Piston/Liner Clearance	No	No	No	No	Yes	Yes	Yes
Installed Oil Delivery to Piston Pin	No	No	No	No	Yes	Yes	Yes
Installed Oil Delivery to Piston Undercrown	No	No	No	No	Yes	Yes(incrsd)	Yes
Increased Oil Charge	No	No	No	No	No	Yes	Yes
Increased Ring Side Clearance	No	No	No	No	No	No	Yes
Results							
Piston Stuck in Liner	No	No	No	Yes	Yes	No	No
Rings Stuck (Number stuck)	No	No	No	Yes(3)	Yes(3)	Yes(3)	Yes(2)
Wrist Pin Stuck in Piston	No	No	No	Yes	Tight	No	No
Stopped Test--High Blowby	No	No	No	---	---	Yes @ 1 hr 18% of Oil Consumed	Yes @ 2.5 hr 24% of Oil Consumed



	NEW PISTON	MACHINED PISTON
LINER BORE, IN.	3.8010	3.8010
PISTON, IN.	3.7956	3.7830
PISTON/LINER CLEARANCE, IN.	0.0054	0.0180

FIGURE 4. CLR-D PISTON

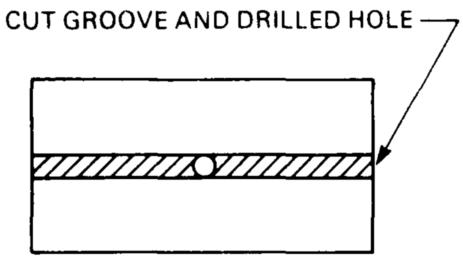


FIGURE 5. CONNECTING ROD BEARING TOP

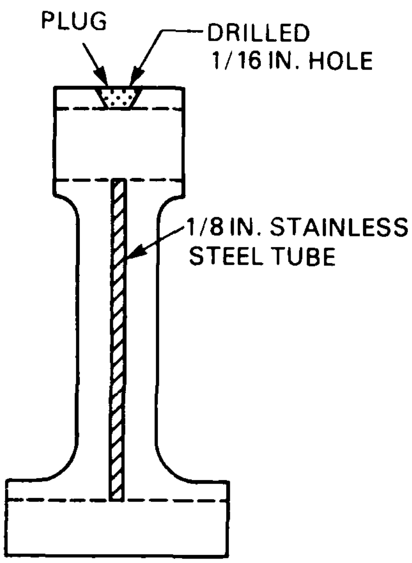


FIGURE 6. CONNECTING ROD

in slightly less severe ring sticking with a maximum liner temperature of 343°C.

A series of CLR-D tests were conducted following the conditions of Test No. 7 to determine if this procedure could discriminate the performance of four different lubricants. The four diesel engine test lubricants were:

- AL-6942, an experimental poly-alphaolefin/polyolester-based oil (Test No. 8)
- REO-203, a petroleum-based reference oil (Test No. 9)
- AL-8423, an ester-based oil (Test No. 10)
- AL-8925, a diester-based Arctic engine oil (Test No. 11)

Engine operating conditions such as load and air/fuel ratio were varied to provide relatively constant cylinder wall temperature which was a primary objec-

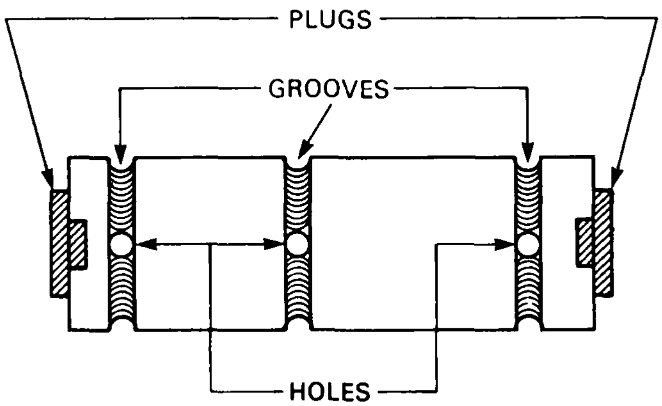


FIGURE 7. WRIST PIN

tive. The tests were run until the oil or engine condition had degraded sufficiently to warrant stopping the test. At end-of-test, the engine was disassembled and rated for deposits, ring sticking, and visual wear. The used oil was analyzed to determine oil degradation. Table 4 contains the results for these tests. Lubricants AL-6942, REO-203, and AL-8423 all showed varying amounts of severe oxidation as evidenced by oil thickening and acid number increase and varying amounts of high oil consumption, bearing corrosion, and ring sticking. These problems are all directly related to high-temperature operation and are representative of problems which might be encountered in the adiabatic diesel engine. Lubricant AL-8925, which contains no zinc dithiophosphate (ZDDP), survived 31.5 hours of high-temperature testing without excessive oil thickening, TAN increase, or piston deposits; however, high oil consumption was observed.

Overall, this series of tests demonstrated that the CLR-D engine test procedure would be useful for evaluating high-temperature engine oil candidates. Key problem areas identified were oil oxidation, ring sticking, bearing corrosion, and oil consumption.

While the CLR-D engine was suitable for high-temperature operation, better test control was desired. Cylinder wall temperature was being controlled by varying the fuel (energy) input, which resulted in fairly consistent liner temperatures; however, other test conditions were varying excessively. To solve this problem, a system was installed by which the liner temperature was adjusted using electric heat while keeping the fuel rate constant. An aluminum sleeve was machined to fit around the CLR-D cylinder liner. The sleeve was drilled and fitted with electrical heating elements so that the liner temperature was controlled without adjusting fuel input. Cylinder liner surface temperature was monitored by 12 iron-constantan thermocouples embedded in the liner. As previously discussed, the thermocouples were installed by drilling a hole through the liner and welding the thermocouple inside the liner at the surface. The liner was then honed to remove surface roughness resulting at the welds. Thermocouples were located approximately 0.5, 2, and 3 inches from the top of the liner at thrust, anti-thrust, front, and back positions as shown in Figure 8. The test procedure was

TABLE 4. CLR-DIESEL HIGH-TEMPERATURE ENGINE TESTS

Test Number:	8	9	10	11
Lubricant Code:	AL-6942	REO-203	AL-8423	AL-8925
Lubricant Type:	PAO/Polyolester	Petroleum	Ester	Diester
Operating Conditions				
RPM	2000	2000	2000	2000
Load, lb	16(9@EOT)	19	20	19
Air/Fuel Ratio	22.5-25.5	12.8-25.5	23.8	24.1-25.5
Coolant Temp in Head, °C(°F)	54(130)	55(131)	54(129)	56(132)
Oil Temp (gallery), °C(°F)	163(3260	162(323)	167(332)	155(311)
Avg Liner Temp, °C(°F)	338(640)	357(675)	357(675)	346(655)
Results				
Test Hours	16	16	9.5	31.5
Oil Consumed, kg(lb)	3.1(6.8)	5.0(11.1)	3.4(7.4)	8.5(18.7)
Oil Consumption, kg/hr	0.194	0.312	0.358	0.270
Ring Sticking				
No. 1 Compress.	Sluggish	100% Cold Stuck	60% Hot Stuck	Free
No. 2 Compress.	25% Cold Stuck	100% Cold Stuck	20% Hot Stuck	Free
Oil Ring	20% Cold Stuck	100% Cold Stuck	100% Cold Stuck	100% Cold Stuck
Deposits				
Piston WTD	331	475	363	286
Piston Skirt Demerits				
Thrust	7.5	7.8	4.6	7.3
Anti-thrust	8.5	8.5	4.4	5.6
Other	---	High Blowby	High Blowby	---
	High Oil Press.	High Oil Press.	---	---

Lubricant Properties	New	Used	New	Used	New	Used	New	Used
K Vis, 40°C, cSt	65	3897	104	Solid	78	398	26	155
K Vis, 100°C, cSt	10.2	178.2	11.8	747	13.0	41	5.9	26.6
TAN	3.7	9.5	3.6	14.8	5.2	13.2	0.2	1.0
TBN (D 664)	10.2	4.6	5.4	4.3	11.2	7.5	7.6	15.0
Wear Metals, ppm		Used		Used		Used		Used
Fe		293		392		296		138
Cu		257		60		72		0
Pb		200		129		100		0
Cr		11		38		0		0
Insolubles "B", wt%		1.1		7.4		1.6		6.2
Toluene		0.8		6.2		1.4		5.7

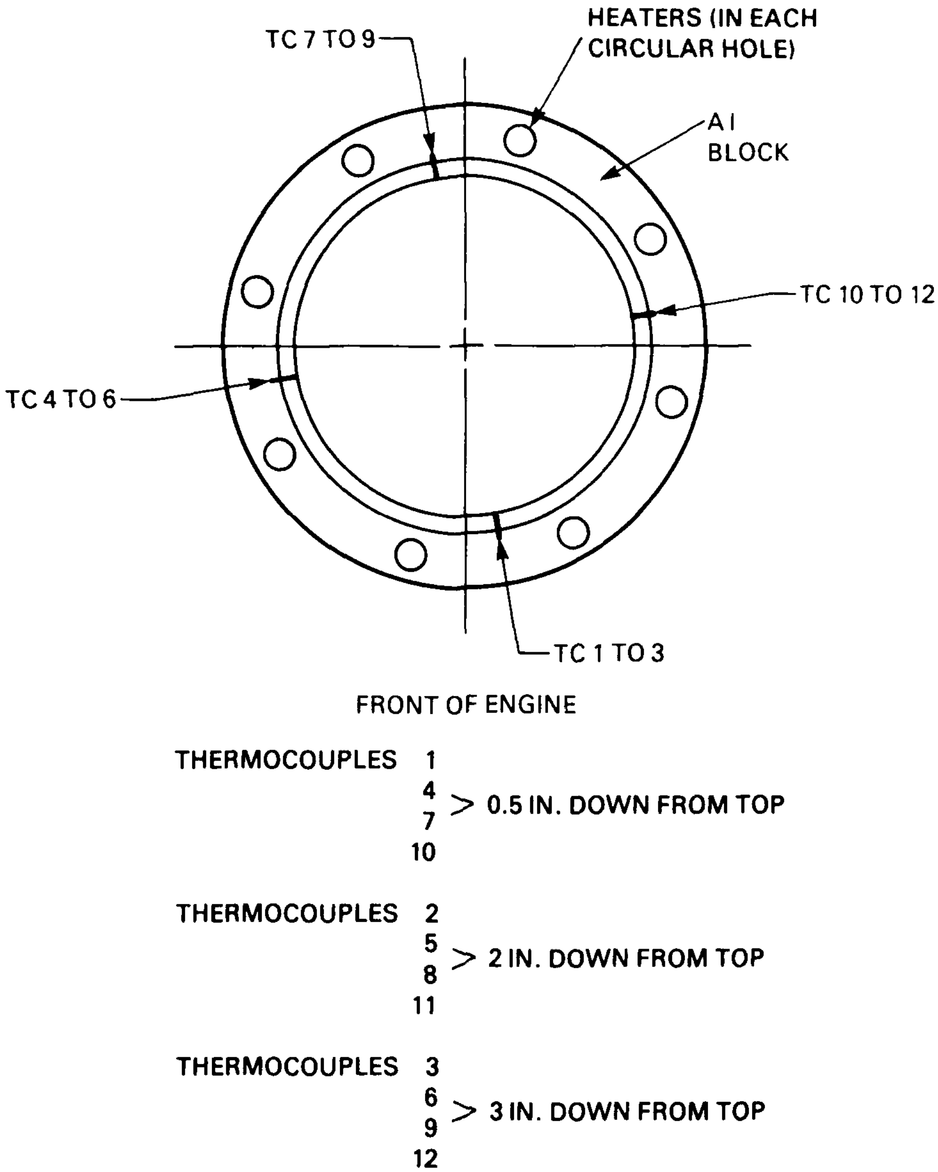


FIGURE 8. ALUMINUM BLOCK WITH HEATERS AND THERMOCOUPLE POSITIONS

modified slightly to achieve approximately 343°C (650°F) average liner surface temperature with an air/fuel ratio of 30. Candidate high-temperature lubricants were screened following this test procedure. Tests A1, A2, and A3 were run without controlling the engine sump oil temperature. Discussions with representatives of Cummins Engine Company revealed that they were planning to incorporate oil coolers on the Army version of their minimum-cooled diesel engine to control oil sump temperature to a maximum of 132°C (270°F). Thus, an external oil cooler was installed on the CLR-D

engine, and all tests with a test number higher than A3 were run with the oil sump temperature controlled at 132°C.

D. High-Temperature Lubricant Evaluations

Potential high-temperature lubricants were evaluated using the CLR-D engine procedure which included the aluminum block heating sleeve as described in the previous section. Test lubricants were obtained from the following sources:

- Commercially available lubricants;
- Candidate lubricants submitted by additive/chemical companies;
- Experimental oil blends prepared by AFLRL.

Appendix A contains the new oil properties for each lubricant tested. Physical properties such as viscosity, additive element content, and volatility by gas chromatographic boiling point distribution were obtained to characterize the test lubricants.

Based on high-temperature problems reported by Cummins (1-4), AFLRL's initial approach was to obtain and evaluate a variety of commercially available synthetic oils having properties which indicated they would be suitable for high-temperature use. The summarized results of this series of CLR-D engine evaluations are presented in Table 5. The first lubricant to be evaluated was AL-8925 which had promising performance during test development runs. AL-8925 is a qualified MIL-L-46167 Arctic engine oil which is diester-based and contains no zinc dithiophosphate. Test A1 completed the scheduled 49 hours and, as in previous tests using AL-8925, oil consumption was rather high (0.66 lb/hr), and the oil control ring was cold stuck. At end-of-test, AL-8925 had thickened considerably, and the total base number had approximately doubled due to concentration of the barium detergent-dispersant additive in the crankcase as lighter ends of the oil were consumed. Much of the oil viscosity increase was due to insolubles concentrating in the used oil. After insolubles removal, the viscosity of the used oil had increased

TABLE 5. CLR-D TESTS -- SYNTHETIC OILS

Test Number:	A1	A5	A7	A8	A24	A10	A16	A17	A20
Lubricant Code:	AL-8925	AL-7135	AL-11507	AL-11507	AL-11507	AL-8924	AL-11761	AL-10690	AL-11848
Lubricant Type:	Ester	Polyolesters	Polyolesters	Polyolesters	Polyolesters	PAO/Ester	Ester	PAB	Syn
Operating Conditions									
RPM	2000	2000	2000	2000	2000	2000	2000	2000	2000
Load, lb/ft	8.2	13.7	14.6	14.5	13.1	15	13.9	11.8	13.1
Air/Fuel Ratio	30:1	30:1	30:1	30:1	30:1	30:1	30:1	30:1	30:1
Coolant Temp in Head, °C(°F)	151(303)	156(313)	157(314)	150(302)	152(306)	151(303)	154(310)	158(317)	154(309)
Oil Temp, °C(°F)	159(318)	132(270)	132(270)	134(274)	133(271)	131(268)	132(270)	132(270)	132(269)
Liner Temp, °C(°F)									
Avg	324(616)	327(620)	332(630)	335(639)	328(623)	336(637)	334(634)	339(642)	343(650)
Min	298(568)	297(566)	309(589)	306(582)	303(577)	316(600)	301(574)	306(583)	317(602)
Max	351(663)	345(653)	357(675)	358(676)	371(700)	357(674)	358(676)	358(677)	3[illegible](688)
Exhaust Temp, °C(°F)	477(891)	481(897)	465(869)	464(867)	469(877)	469(876)	481(897)	506(942)	478(893)
Results									
Test Hours	49	10	17	13	12	17	48	16	45
Oil Consumed, kg(lb)	14.6(32.1)	0.7(1.5)	1.5(3.4)	1.8(4.0)	1.8(3.9)	2.6(5.7)	8.2(18.1)	8.6(3.9)	6.5(14.4)
Ring Sticking									
No. 1 Compress.	Free	30 CS	Free	Free	Free	Free	Free	Free	Free
No. 2 Compress.	Free	100 CS	15 CS	100 CS	100 CS	Free	Sluggish	Free	Sluggish
Oil Ring	100 CS	100 CS	100 CS	100 CS	100 CS	100 CS	100 CS	100 CS	100 CS
Deposits									
Piston WTD	266	342	245	150	321	208	301	278	173
Piston Skirt Demerits									
Thrust	8.5	5.2	3.5	3.2	3.0	5.5	2.5	6.0	3.5
Anti-Thrust	7.5	4.0	3.5	3.5	2.8	5.0	2.0	4.5	3.0
Other									
Oil Consumption, lb/hr	0.655	0.15	0.2	0.31	0.32	0.34	0.38	0.54	0.32
As % of fuel + oil rate	17	4	6	9	9	10	11	16	9

Lubricant Properties	A1 New	A1 Used	A5 New	A5 Used	A7 New	A7 Used	A8 New	A8 Used	A24 New	A24 Used	A10 New	A10 Used	A16 New	A16 Used	A17 New	A17 Used	A20 New	A20 Used
K Vis, 40°C, cSt	26	207.7	67.5	95.4	61.9	155.6	61.9	242.1	61.9	149.6	56.0	112.7	63.3	2248	30.32	72.0	133.0	2972
K Vis, 100°C, cSt	5.9	32.8	10.0	12.8	9.6	17.9	9.6	24.1	9.6	18.3	10.0	14.6	10.7	114.5	6.10	11.3	17.8	162.2
Flash Point, °C	234	252	227	271	263	268	263	262	263	264	224	232	221	238	221	221	227	262
TAN	0.2	0.4	2.5	3.2	2.3	7.2	2.3	8.6	2.3	6.4	3.0	9.0	3.8	16.5	3.3	8.2	1.6	2.7
TBN (D 664)	7.6	14.1	7.9	4.4	7.4	4.7	7.4	3.7	7.4	4.9	6.3	2.8	13.2	12.4	6.4	6.1	10.6	10.8

Wear Metals, ppm	A1 Used	A5 Used	A7 Used	A8 Used	A24 Used	A10 Used	A16 Used	A17 Used	A20 Used
Fe	62	138	117	85	109	72	45	431	17
Cu	12	37	175	50	<10	136	24	486	10
Pb	40	60	710	684	102	391	<60	397	<60
Insolubles "B", wt%									
Pentane	10.0	0.2	0.1	0.1	0.87	0.2	0.47	3.4	0.18
Toluene	8.4	0.2	0.1	0.1	0.77	0.1	0.42	2.9	0.17
Differential in Oxidation Absorbance at 1710 CM^{-1}	0.08	0.09	ND	ND	0.38	ND	0.51	0.42	ND
Other	OK	OK	Bearing Corrosion	Bearing Corrosion	OK	Bearing Corrosion	OK	Bearing Corrosion	OK

ND - Not Determined
CS - Cold Stuck

only 30 percent. Oil oxidation was not excessive as determined by differential infrared analysis and total acid number increase. Despite high oil consumption and oil ring sticking, AL-8925 did complete the scheduled 49 test hours.

AL-7135, a synthetic polyolester-based diesel engine oil which had excellent high-temperature volatility properties, was evaluated in Test A-5. The test was stopped after 10 of a scheduled 49 hours due to erratic engine operating conditions. Oil consumption was relatively low with lubricant AL-7135, and the used oil was not severely oxidized; however, post-test inspection revealed stuck rings. Another polyolester-based engine oil (AL-11507) which was a close relative of AL-7135 was tested three times (Tests Nos. A7, A8, and A24). AL-11507 is a commercially available 10W30 oil which was submitted by Cummins Engine Company and had shown promise in Cummins' screening tests. Test A7 was stopped after 17 of a scheduled 49 hours due to high copper and lead content in the used oil, which resulted from connecting rod and main bearing corrosion. The oil was retested (Test A8) and had completed 13 hours when the same problem occurred. The used oils from both tests had high total acid numbers (>7); however, in subsequent tests of different oils, higher acid numbers were observed without bearing distress. A third test of AL-11507 (Test A24) was stopped at 12 hours as the used oil lead content had started to increase. In all tests of AL-11507, compression ring cold sticking was a problem, and oil consumption was relatively mild compared to AL-8925. Another commercially available synthetic diesel engine oil (AL-8924) was evaluated in Test No. A10. AL-8924 had a polyalphaolefin (PAO)/polyolester blend basestock. The test was terminated at 17 hours due to high copper and lead content in the used oil. Engine inspection revealed bearing corrosion as in the tests of AL-11507. AL-8924 was slightly superior to AL-11507 in that no compression ring sticking was observed. It appears that the compression ring sticking observed with polyolester engine oils is due to their low volatility which allows the oil to remain in the high-temperature ring belt zone and coke as opposed to volatilizing and burning off as the more volatile oils do.

A diester-based commercially available diesel engine oil (AL-11761) was evaluated in Test A16. Oil AL-11761 completed 48 test hours and exhibited much lower oil consumption than AL-8925; however, AL-11761 had oxidized severely and had a final drain total acid number of 16.5. Apparently, the acidic materials resulting from oil decomposition and oxidation were not harmful as no bearing corrosion was observed. Overall, AL-11761 was one of the more promising high-temperature candidate oils.

Test A17 used a different MIL-L-46167 Arctic engine oil (AL-10690) which contained a polyalkylated benzene (PAB) basestock. Oil consumption was high, and the used oil contained excessive amounts of iron, copper, and lead when the test was terminated at 16 hours. Bearing corrosion was found when the engine was inspected. Based on this test, oil AL-10690 is not recommended for high-temperature use.

The final commercially available synthetic oil tested was AL-11848, which contained a basestock blend of diester and PAO and was formulated for use as a manual transmission fluid. While this oil contains no zinc antiwear additive, the manufacturer claims the oil meets API diesel engine service classification CD. AL-11848 had very good performance in CLR-D test No. A20. The used oil had thickened substantially, but the TAN had not increased and wear metal accumulation in the used oil was very low. Oil consumption was moderate, piston deposits were low, and compression rings were not stuck. The performance of AL-11848 in the high-temperature CLR-D test was the best overall of the commercially available oils tested; however, it did not exhibit adequate control of viscosity increase.

Three CLR-D tests were conducted to develop baseline performance data on conventional petroleum-based lubricants. The summarized results are presented in Table 6. Oil AL-8980, the Army's MIL-L-2104C Reference Oil, was evaluated in Test A11. This test completed 33.5 of a scheduled 49 hours when it was stopped due to severe oil thickening. Oil consumption was moderate with this SAE 30 grade viscosity product. Post-test oil analyses revealed extreme oil viscosity increase, TAN increase, and oil oxidation by differential infrared analysis. The bearing corrosion observed in some

TABLE 6. CLR-D TESTS -- PETROLEUM-BASED OILS

Test Number:	A11		A21		A25	
Lubricant Code:	AL-8980		AL-11788		AL-10605	
Lubricant Type:	Petroleum		Petroleum		Petroleum	
Operating Conditions						
RPM	2000		2000		2000	
Load, lb/ft	13.8		11.5		13.0	
Air/Fuel Ratio	30:1		30:1		30:1	
Coolant Temp in Heat, °C(°F)	147(296)		154(310)		154(309)	
Oil Temp, °C(°F)	133(271)		130(266)		132(269)	
Liner Temp, °C(°F)						
Avg	334(633)		338(641)		327(620)	
Min	310(590)		308(586)		299(571)	
Max	355(671)		374(706)		364(688)	
Exhaust Temp, °C(°F)	444(832)		501(933)		505(941)	
Results						
Test Hours	33.5		21		30	
Oil Consumed, kg(lb)	4.8(10.5)		6.2(13.6)		7.9(17.5)	
Ring Sticking						
No. 1 Compress.	Free		Sluggish		Free	
No. 2 Compress.	100% CS		100% CS		100% CS	
Oil Ring	100% CS		100% CS		100% CS	
Deposits						
Piston WTD	313		401		285	
Piston Skirt Demerits						
Thrust	3.0		5.0		8.5	
Anti-Thrust	2.8		6.5		7.8	
Other						
Oil Consumption, lb/hr	0.31		0.65		0.58	
as of % of fuel + oil rate	9		17		16	
Lubricant Properties	New	Used	New	Used	New	Used
K Vis, 40°C, cSt	109	3377	110.0	ND	113.2	4460
K Vis, 100°C, cSt	11.7	90.7	14.6	1900	14.8	141.8
Flash Point, °C	223	229	221	218	218	236
TAN	2.3	6.8	3.0	14.2	2.3	13.9
TBN (D 664)	13.3	8.2	5.7	4.8	10.2	14.7
Wear Metals, ppm	Used		Used		Used	
Fe	46		111		120	
Cu	21		33		<10	
Pb	<60		65		<60	
Insolubles "B", wt%						
Pentane	2.3		0.98		1.16	
Toluene	1.6		0.80		1.03	
Differential IR Oxidation Absorbance at 1710 CM^{-1}	0.57		0.54		0.78	
Other	OK		OK		OK	

ND - Not Determined

CS - Cold Stuck

previous tests which utilized synthetic oils was not present. While the performance of AL-8980 was not adequate; overall, it was better than expected considering that the oil was not specially formulated for high-temperature service. A 15W-40 petroleum-based diesel engine oil (AL-11788) was run in Test A21. At 21 hours, the test was stopped because of oil thickening. Oil consumption was high, piston deposits were heavy, and the used oil had a TAN of 14.2; however, no bearing distress was observed. Test A25 (AL-10605) was run to obtain baseline data on how a multigrade oil of MIL-L-2104D quality level would perform at the high-temperature conditions of the CLR-D test. At 30 hours, the test was stopped due to oil thickening and erratic operation. Post-test analyses revealed that the oil was severely oxidized with a TAN of 13.9. Oil consumption was high, and the total base number had increased during the test indicating a concentration of additive components as lighter ends of the lubricant were consumed. Overall, the high-temperature performance of the multiviscosity grade MIL-L-2104D quality oil was similar to other petroleum-based lubricants which were tested in the CLR-D.

Several additive and chemical companies were contacted and requested to submit candidate high-temperature lubricants for evaluation in the CLR-D engine test. Excellent response and cooperation were obtained from three companies.

Company A provided four candidates which were evaluated in the CLR-D high-temperature test. The summarized results of these four tests are presented in Table 7. Oil AL-11661 (Test A12) contained a PAO basestock, calcium/magnesium detergent-dispersant system, alkyl zinc dithiophosphate, and had a sulfated ash content of 0.8 wt%. The test was stopped at 8.5 hours due to very high copper and lead in the used oil, and bearing corrosion was confirmed upon engine inspection. Oil AL-11662 (Test A19) contained the same additive system as AL-11661 except that some of the zinc dithiophosphate was aryl type. The basestock was a blend of 80 percent PAO and 20 percent bright stock. Oil consumption was improved over Test A12; however, the test was stopped at 26 hours due to high copper and lead content in the used oil. Once again, bearing corrosion was found. Oil AL-11663 (Test A14) contained

TABLE 7. CLR-D TESTS -- OILS FROM COMPANY A

Test Number:	A12		A19		A14		A15	
Lubricant Code:	AL-11661		AL-11662		AL-11663		AL-11723	
Lubricant Type:	PAO		Pet/PAO/ Aryl Zn		Petroleum		PAO	
Operating Conditions								
RPM	2000		2000		2000		2000	
Load, lb/ft	14.8		12.5		14.4		14.2	
Air/Fuel Ratio	30:1		30:1		30:1		30:1	
Coolant Temp in Head, °C(°F)	152(305)		152(306)		152(306)		155(311)	
Oil Temp, °C(°F)	132(270)		132(270)		153(306)		133(272)	
Liner Temp, °C(°F)								
Avg	330(626)		327(621)		132(270)		339(643)	
Min	312(593)		306(582)		337(638)		321(610)	
Max	349(661)		358(677)		311(592)		360(680)	
Exhaust Temp, °C(°F)	463(866)		484(903)		491(915)		488(911)	
Results								
Test Hours	8.5		26		19		21	
Oil Consumed, kg(lb)	2.1(4.7)		2.8(6.2)		4.5(9.9)		2.6(5.7)	
Ring Sticking								
No. 1 Compress.	Free		Sluggish		Free		Free	
No. 2 Compress.	100 CS		100 CS		100 CS		75 CS	
Oil Ring	100 CS		Sluggish		100 CS		100 CS	
Deposits								
Piston WTD	194		242		288		245	
Piston Skirt Demerits								
Thrust	3.3		6.0		3.5		4.5	
Anti-Thrust	3.6		7.0		4.0		5.5	
Other								
Oil Consumption lb/hr	0.5		0.24		0.52		0.27	
as % of fuel + oil rate	16		7		15		8	
Lubricant Properties	New	Used	New	Used	New	Used	New	Used
K Vis, 40°C, cSt	79.4	260	85.7	765.9	98.2	ND	76.8	645.3
K Vis, 100°C, cSt	11.6	26.8	11.5	52.4	11.3	100.8	11.4	50.1
Flash Point, °C	239	241	242	252			251	254
TAN	3.0	5.5	3.0	10.4	2.5	10.6	3.0	11.2
TBN (D 664)	5.5	2.9	5.6	2.3	7.5	16.1	7.0	4.1
Wear Metals, ppm	Used		Used		Used		Used	
Fe	33		203		56		74	
Cu	171		110		39		216	
Pb	361		356		187		588	
Insolubles "B", wt%								
Pentane	0.1		0.36		0.2		0.17	
Toluene	0.1		0.32		0.2		0.15	
Differential IR Oxidation Absorbance at 1710 CM^{-1}:	0.16		0.75		0.73		1.0	
Other	Bearing Corrosion		Bearing Corrosion		OK		Bearing Corrosion	

ND - Not Determined; CS - % Cold Stuck

all petroleum-base stock including 30 percent bright stock and a detergent-dispersant consisting primarily of magnesium with a small amount of calcium, which resulted in an oil with a sulfated ash content of 1 wt%. Test A14 was terminated at 19 hours because of oil thickening and TAN increase. The final candidate oil from Company A was AL-11723 which was formulated to have improved diesel engine performance. It contained a PAO base stock and a calcium/magnesium additive system. Test A15 (AL-11723) was stopped at 21 of a scheduled 49 hours due to extremely high lead and copper content in the used oil. Oil consumption was moderate during this test but, again, bearing corrosion was a major problem. None of the experimental lubricants received from Company A had adequate performance in the high-temperature CLR-D engine test.

Company B submitted eight experimental high-temperature candidate lubricants. Oil AL-11147 was a PAO-based material which was heavily treated with additives. It was an SAE 50 grade viscosity oil, contained 1 wt% calcium, and had a sulfated ash content of 3.2 wt%. AL-11147 was evaluated in tests A2 and A4, and the results are shown in Table 8. In Test A2, the oil sump temperature was uncontrolled and averaged 174°C while, in Test A4, it was controlled to 132°C. Test A2 was stopped at 24 hours due to oil solidification which resulted from severe oil oxidation. The used oil had a TAN of 13.6, further indicating that the solidification was the result of oxidation and not soot accumulation. Test A4 was stopped at 25 hours due to severe oil thickening, and the used oil had a TAN of 13.0. Oil consumption was fairly low in both tests. By comparing the results of tests A2 and A4, it appears that most of the oil oxidation is caused when the oil film is exposed to the hot cylinder wall, because the reduced oil sump temperature in Test A4 did not appreciably extend oil life. A revised oil formulation (AL-11683) was submitted by Company B which contained only PAO basestock and no petroleum diluent oil from the additive package. This oil was an SAE 40 viscosity grade with 0.4 wt% calcium and a sulfated ash content of 1.9 wt%. Test A13 (AL-11683) was stopped at 30.5 hours when the oil solidified. Post-test engine inspection also showed bearing corrosion to be present.

TABLE 8. CLR-D TESTS -- OILS FROM COMPANY B

Test Number:	A2		A4		A13	
Lubricant Code:	AL-11147		AL-11147		AL-11683	
Lubricant Type:	PAO		PAO		PAO	
Operating Conditions						
RPM	2000		2000		2000	
Load, lb/ft	8.5		10.2		13.9	
Air/Fuel Ratio	30:1		30:1		30:1	
Coolant Temp in Head, °C(°F)	150(302)		152(305)		151(304)	
Oil Temp, °C(°F)	174(345)		132(270)		132(270)	
Liner Temp, °C(°F)						
Avg	332(630)		330(626)		342(647)	
Min	304(580)		311(591)		319(607)	
Max	343(649)		346(655)		357(674)	
Exhaust Temp, °C(°F)	443(829)		463(866)		466(870)	
Results						
Test Hours	24		25		30.5	
Oil Consumed, kg(lb)	a		2.1(4.7)		a	
Ring Sticking						
No. 1 Compress.	Free		Free		Sluggish	
No. 2 Compress.	100 CS		100 CS		100 CS	
Oil Ring	100 CS		100 CS		100 CS	
Deposits						
Piston WTD	274		368		253	
Piston Skirt Demerits						
Thrust	5.0		4.5		7.5	
Anti-Thrust	5.6		3.8		6.0	
Other						
Oil Consumption, lb/hr	0.20 est		0.18		0.25 est	
as of % of fuel + oil rate	6		5		7	
Lubricant Properties	New	Used	New	Used	New	Used
K Vis, 40°C, cSt	182.8	a	182.8	26400	119.8	a
K Vis, 100°C, cSt	19.5	a	19.5	266.3	15.3	a
Flash Point, °C	258	a	258	232	247	a
TAN	4.6	13.6	4.6	13.0	2.6	12.2
TBN (D 664)	13.5	6.6	13.5	6.5	12.8	5.9
Wear Metals, ppm	Used		Used		Used	
Fe	167		134		104	
Cu	49		33		97	
Pb	260		101		345	
Insolubles "B", wt%						
Pentane	a		1.2		a	
Toluene	a		1.1		a	
Differential IR Oxidation Absorbance at 1710 CM^{-1}:	0.48		0.38		1.25	
Other					Bearing Corrosion	

CS - % Cold Stuck

a - Not determined, oil solidified

A series of lubricants were submitted by Company B in which each oil was formulated with the same additive treatment level and a different basestock material. The following list identifies the oils:

Code No.	Basestock Type	CLR-D Test No.
AL-11873	4 cSt PAO	Not tested
AL-11874	6 cSt PAO	A28
AL-11875	Trimethylolpropane Ester	A23
AL-11876	Diester	A29
AL-11877	Mineral Oil	A22
AL-11878	Alkyl Diphenylether	A27

The oils were all formulated with the same additive package to have the following properties:

Ca, wt%	0.49
Zn, wt%	0.11
P, wt%	0.08
Sulfated Ash, wt%	1.8
TBN (D664)	13

Oil AL-11875 (TMP ester) was found to be slightly low in additive content but was included in the test program.

The oils were evaluated in the CLR-D test to determine which basestock type had the best performance at high temperatures which simulate the conditions of the adiabatic diesel engine. The summarized test results are shown in Table 9.

Petroleum-based oil AL-11877 completed 40.5 of a scheduled 49 test hours (Test A22) and was stopped due to oil thickening. While test A23 (TMP basestock) was stopped at 42 hours due to erratic operation caused by compression ring sticking, Test A27 (diphenylether) completed the 49 hours. Test A28 (PAO-6CS) was stopped at 40 hours due to breakage of the top compression ring, which was considered a nonlubricant-related failure. The

TABLE 9. CLR-D TESTS -- BASESTOCK VARIATIONS FROM COMPANY B

Test Number:	A22	A23	A27	A28	A29
Lubricant Code:	AL-11877	AL-11875	AL-11878	AL-11874	AL-11876
Lubricant Type:	Petroleum	TMP	Diphenyl Ether	PAO	Diester
Operating Conditions					
RPM	2000	2000	2000	2000	2000
Load, lb/ft	13.9	11.3	13.5	12.5	10.6
Air/Fuel Ratio	30:1	30:1	30:1	30:1	30:1
Coolant Temp in Head, °C(°F)	156(313)	157(314)	153(307)	153(308)	152(306)
Oil Temp, (Sump), °C(°F)	132(269)	133(271)	133(271)	133(271)	132(270)
Liner Temp, °C(°F)					
Avg	330(626)	334(633)	335(635)	332(629)	334(633)
Min	299(571)	304(580)	292(558)	296(564)	305(581)
Max	364(688)	360(680)	350(662)	355(671)	356(673)
Exhaust Temp, °C(°F)	503(937)	474(886)	478(892)	492(917)	440(825)
Results					
Test Hours	40.5	42	49	40	40
Oil Consumed, kg(lb)	12.4(27.3)	10.8(23.9)	6.2(13.8)	6.1(13.5)	10.9(24.0)
Ring Sticking					
No. 1 Compress.	Free	100 CS	Free	Broken	Free
No. 2 Compress.	Sluggish	100 CS	Free	30 CS	75 CS
Oil Ring	100 CS	100 CS	100 CS	100 CS	100 CS
Deposits					
Piston WTD	300	313	360	361	328
Piston Skirt Demerits					
Thrust	2.5	2.0	2.0	2.8	7.5
Anti-Thrust	2.0	2.0	5.0	3.0	7.0
Other					
Oil Consumption lb/hr	0.67	0.57	0.28	0.34	0.60
As % of fuel + oil rate	18	16	8	10	16

Lubricant Properties	A22 New	A22 Used	A23 New	A23 Used	A27 New	A27 Used	A28 New	A28 Used	A29 New	A29 Used
K Vis, 40°C, cSt	50.1	4785	21.8	445.6	81.8	453.9	47.4	287.1	17.2	453.7
K Vis, 100°C, cSt	7.2	151.9	4.8	41.3	9.3	31.8	7.7	27.6	4.2	47.0
Flash Point, °C	222	234	232	229	232	241	229	246	221	235
TAN	3.6	14.5	3.6	11.6	3.8	11.6	3.9	11.1	3.6	11.1
TBN (D 664)	13.2	19.1	11.9	16.4	13.6	13.4	13.3	11.9	12.8	17.6

Wear Metals, ppm	A22 Used	A23 Used	A27 Used	A28 Used	A29 Used
Fe	56	116	121	81	70
Cu	13	27	<10	<10	<10
Pb	<60	<60	<60	<60	<60
Insolubles "B", wt%					
Pentane	1.01	1.35	0.39	1.43	2.27
Toluene	0.95	1.28	0.36	1.28	2.05
Diff. IR OX(1710cm^{-1})	0.48	ND	0.36	0.16	0.34
				Top Ring Broke-Stopped Test Prematurely	

ND - Not Determined
CS - % Cold Stuck

diester basestock (Test A29) had completed 40 hours when the supply of make-up oil was consumed, and the test was terminated. The petroleum-based oil was the only case where oil thickening was extreme. The other four basestock materials thickened considerably during their respective tests but not to the point of interfering with engine operation. All used oils had total acid number (TAN) increase to approximately 11 except for the petroleum oil which had a TAN of 14.5 at end-of-test. Oil consumption was moderate for the diphenylether oil, slightly higher for the PAO oil, and very high for the diester, trimethylolpropane ester (TMP), and petroleum oils. Total base number increased during the test for the oils with very high oil consumption due to additive concentration as lighter ends of the lubricant were consumed. Severe ring sticking was observed with the TMP oil as both compression rings were 100 percent cold stuck. The best ring sticking performance was obtained with the diphenylether oil which had no compression ring sticking. Wear as indicated by used oil iron content was highest for the diphenylether and TMP oils and lowest for the petroleum oil; however, the wear level obtained for all oils was acceptable. Overall, the diphenylether oil performed the best in the high-temperature CLR-D test as evidenced by its relatively low oil consumption rate, mild viscosity increase, and the absence of compression ring sticking.

Three experimental high-temperature lubricants were received from Company C and evaluated in the CLR-D engine test procedure. The summarized results are presented in Table 10. Oil AL-11132 (Test A3) contained polyolester basestock material and was formulated to be essentially ashless with a phosphorus antiwear additive present. Test A3 was stopped after 7 of a scheduled 49 hours due to erratic operating conditions and high blowby. Post-test inspection revealed stuck rings and moderate oil consumption. These results were discussed with the oil supplier, and a novel approach to solving the ring-sticking problem was developed. Test A9 evaluated an experimental oil (AL-11511) from Company C which contained a blend of narrow boiling range ester and polyalkyleneglycol (PAG). The PAG was present to provide a controlled oil consumption which would aid in flashing the relatively nonvolatile ester off the piston to prevent compression ring sticking due to coking of the ester in the ring belt area. Oil AL-11511 contained a

TABLE 10. CLR-D TESTS -- OILS FROM COMPANY C

Test Number:	A3		A9		A26	
Lubricant Code:	AL-11132		AL-11511		AL-11953	
Lubricant Type:	Polyolesters		Ester/PAG*		Polyolesters	
Operating Conditions						
RPM	2000		2000		2000	
Load, lb/ft	10.1		16		14.5	
Air/Fuel Ratio	30:1		29:1		30:1	
Coolant Temp in Head, °C(°F)	148(298)		157(314)		162(323)	
Oil Temp, °C(°F)	173(344)		132(269)		133(271)	
Liner Temp, °C(°F)						
Avg	330(626)		337(639)		337(639)	
Min	307(584)		316(600)		291(555)	
Max	348(659)		359(679)		364(687)	
Exhaust Temp, °C(°F)	391(736)		493(920)		492(917)	
Results						
Test Hours	7		10		11.5	
Oil Consumed, kg(lb)	0.7(1.6)		2.5(5.6)		3.4(7.6)	
Ring Sticking						
No. 1 Compress.	40 CS		100 CS		Free	
No. 2 Compress.	100 CS		100 CS		Free	
Oil Ring	100 CS		100 CS		100 CS	
Deposits						
Piston WTD	285		341		217	
Piston Skirt Demerits						
Thrust	9.0		8.8		2.0	
Anti-Thrust	5.0		8.0		3.5	
Other						
Oil Consumption lb/hr.	0.234		0.53		0.66	
As % of fuel + oil rate	7		16		18	
Lubricant Properties	New	Used	New	Used	New	Used
K Vis, 40°C, cSt	66.9	156.8	43.4	66.1	123.0	300
K Vis, 100°C, cSt	10.6	18.2	8.4	9.7	12.4	24.4
Flash Point, °C	290	296	0	10.5	240	252
TAN	0.7	5.1	2.1	0.3	3.0	9.8
TBN (D 664)	0.0	0.1	2.1	0.3	6.4	5.6
Wear Metals, ppm	Used		Used		Used	
Fe	71		254		1441	
Cu	29		17		25	
Pb	105		147		<60	
Insolubles "B", wt%						
Pentane	0.3		2.3		0.55	
Toluene	0.2		0.1		0.50	
Diff. IR OX(1710 cm^{-1})	0.50		ND		0.14	
					Piston Scuffing Thrust Side = 80%	

* - polyalkyleneglycol
ND - Not Determined
CS - % Cold Stuck

phosphorus antiwear additive and 0.05 wt% calcium detergent-dispersant agent, which resulted in the oil having a sulfated ash content of 0.28 wt%. Unfortunately, this formulation was not successful, as severe ring sticking occurred within 10 hours. Also, the iron content of the used oil was rather high at 254 PPM. The third oil (AL-11953) received from Company C was a polyolester-based material which contained calcium and zinc additives and had a sulfated ash content of 0.89 wt%. Test A26 was stopped at 11.5 hours due to very high iron content in the used oil. Disassembly and inspection of the engine revealed heavy piston/liner wear. Piston thrust side had 80 percent scuffing, and both the cylinder and liner had to be replaced for the next CLR-D test. Test A26 demonstrated the need for a bench-wear screening technique.

The results of the final group of miscellaneous experimental lubricants to be tested in the high-temperature CLR-D engine are summarized in Table 11. Test A6 was an evaluation of high-temperature candidate oil (AL-11386) submitted by Cummins Engine Company. This experimental PAO/ester hybrid oil has shown promise in Cummins high-temperature bench screening tests. Oil consumption during test A6 was low; however, the test was stopped after 26 of a scheduled 49 hours due to high blowby and erratic operation. Inspection of the engine revealed cold stuck compression rings. The stuck rings were removed, and the piston was cleaned. New piston rings were installed, and the test was continued using the same engine oil. After 6 additional test hours, the oil viscosity had increased substantially which prevented further operation. Post-test examination revealed stuck piston rings and severe oil oxidation accompanied by TAN increase and bearing corrosion.

Based on antioxidant screening tests, as discussed in the next section, two CLR-D tests were conducted using previously tested oils which were fortified with supplemental antioxidants. The summarized test results are shown in Table 11. Oil AL-11761, which had performed well but still had thickened during Test A16, was fortified with supplemental high-temperature ashless antioxidant (p,p'-dioctyldiphenylamine) and evaluated in CLR-D Test A18. The fortified oil, AL-11797, completed the scheduled 49 hours; however, severe oil oxidation still occurred. Overall, this supplemental antioxidant

TABLE 11. CLR-D TESTS -- MISCELLANEOUS OIL BLENDS

	A18		A30		A31		A6	
Test Number:	A18		A30		A31		A6	
Lubricant Code:	AL-11797		AL-12187		AL-12202		AL-11386	
Lubricant Type:	Syn+Supplm Antiox		Syn+Supplm Antiox		Syn Blend Ester/Phos.		PAO/Ester	
Operating Conditions								
RPM	2000		2000		2000		2000	
Load, lb/ft	12.7		12.3		13.3		14.4	
Air/Fuel Ratio	30:1		30:1		30:1		30:1	
Coolant Temp in Head, °C(°F)	152(305)		154(310)		150(302)		154(310)	
Oil Temp, (Sump), °C(°F)	132(270)		133(271)		132(270)		132(270)	
Liner Temp, °C(°F)								
Avg	337(639)		330(626)		331(628)		334(633)	
Min	308(587)		299(571)		302(575)		313(595)	
Max	363(685)		353(668)		346(654)		344(651)	
Exhaust Temp, °C(°F)	482(900)		482(900)		492(917)		463(866)	
Results								
Test Hours	49		41		43		32*	
Oil Consumed, kg(lb)	9.2(20.4)		6.6(14.6)		13.5(29.7)		2.5(5.6)	
Ring Sticking								
No. 1 Compress.	Sluggish		Free		20 CS		70 CS	
No. 2 Compress.	100 CS		Sluggish		100 CS		100 CS	
Oil Ring	100 CS		Sluggish		100 CS		100 CS	
Deposits								
Piston WTD	285		271		416		334	
Piston Skirt Demerits								
Thrust	2.0		2.5		7.8		8.0	
Anti-Thrust	2.8		2.0		9.2		9.0	
Other								
Oil Consumption lb/hr	0.42		0.36		0.69		0.17	
as % of fuel + oil rate	12		10		19		5	
Lubricant Properties	New	Used	New	Used	New	Used	New	Used
K Vis, 40°C, cSt	63.3	12186	133.3	4546	25.2	39.3	157.6	2400
K Vis, 100°C, cSt	10.7	313.1	17.8	211.4	5.0	7.7	19.7	125.6
Flash Point, °C	221	235	227	243	265	265	240	248
TAN	3.8	15.9	1.6	0.9	0.2	2.0	1.6	13.8
TBN (D 664)	13.2	14.2	10.6	8.3	0.1	0.0	7.4	1.1
Wear Metals, ppm	Used		Used		Used		Used	
Fe	86		<10		89		205	
Cu	13		17		25		42	
Pb	<60		<60		<60		221	
Insolubles "B", wt%								
Pentane	0.84		0.49		1.30		0.6	
Toluene	0.79		0.46		0.42		0.4	
Other	OK		OK		OK		Bearing Corrosion	

ND - Not Determined
CS - % Cold Stuck
* - Replaced rings @ 26 hours.

did not improve the high-temperature performance of AL-11761. Oil AL-11848, which was one of the better candidate oils, was supplemented with 2 wt% each of p,p'-dioctyldiphenylamine and phenyl-α-naphthylamine. CLR-D test A30 was conducted using this formulation (AL-12187); however, the addition of these supplemental antioxidants did not improve CLR-D test performance except for a slight reduction in oil control ring sticking.

Test A31 was conducted using AL-12202 which is a blend of 5 cSt synthetic jet turbine oil (90%) and triarylphosphate (10%). This lubricant composition has been used by Garrett Corp. for high-temperature operation in developing a diesel engine core for the compound cycle turbofan engine engine (CCTE) (9). The test was stopped due to erratic operation after completing 43 hours. Subsequent engine inspection revealed very heavy piston deposits and ring sticking. The high oil consumption experienced with AL-12202 probably caused the fuel injector hole plugging which occurred throughout the test. Overall, AL-12202 is not recommended for use in U.S. Army experimental high-temperature diesel engines.

Correlation of oil consumption rate observed in the high-temperature CLR-D tests with oil volatility was attempted using linear regression. Taking the oil 50 percent off boiling point as the independent variable and oil consumption rate as the dependent variable, a correlation coefficient (R^2) of 0.217 was obtained, indicating no strong relationship between these two variables.

Based on the thirty-one high-temperature lubricant screening tests in the CLR-D engine, the following lubricant-related problem areas have been identified:

- Lubricant oxidation--oil too thick to pump; corrosive products formed and bearings attacked; TAN and viscosity increase.
- Lubricant volatility--high oil consumption.
- Engine deposits--ring sticking.

Future work will concentrate on developing a lubricant which solves these problem areas. Having defined lubricant problem areas under simulated adiabatic engine conditions, bench-scale tests for oxidation, volatility, and deposits can be developed to aid in screening candidate oils.

III. BENCH TESTS

As expected, oil oxidation was a lubricant problem observed during the high-temperature CLR-D test. Thus, it was desired to develop a bench-scale methodology to screen candidate lubricants for oxidation stability prior to engine testing. Differential Scanning Calorimetry (DSC) has been used to indicate lubricant oxidation stability.(10,11) DSC is an analytical technique which detects net heat changes in a sample. An oil sample being held at a high temperature can undergo oxidation, which is an exothermic process or evaporation, which is an endothermic process. To reduce evaporation (endothermic effects), high-pressure DSC was used. A duPont Thermal Analyzer Model 990 was used which was equipped with a duPont high-pressure cell. HPDSC operating conditions were:

180°C Isothermal
500 psig oxygen pressure
40 mL/min flow
0.8-1.2 mg sample
Open pan configuration.

Using these conditions, the time to a heat change (break point) varied from less than 10 minutes to greater than 500 minutes for various high-temperature lubricants. Test repeatability was determined for two oils using the open pan procedure. Oil AL-11761 (diester) had a mean time to break point of 121 minutes with a standard deviation of 7 minutes (N = 7 tests), while Oil AL-11662 (PAO/petroleum) had a mean break time of 63 minutes with a standard deviation of 9 minutes (N = 8 tests). While better repeatability would be desirable, this level of repeatability was judged as adequate for screening high-temperature oils, given the broad range of break times observed.

Table 12 presents the HPDSC single-test results for several high-temperature lubricant candidates, most of which have been tested in the CLR-D engine. It is difficult to relate HPDSC results to CLR-D test hours because the CLR-D test hours vary, depending on the reason for stopping the test (e.g., oxidation/oil thickening, bearing corrosion, or stuck rings). However, most, but not all, of the oils which have given good CLR-D performance tended to have longer HPDSC break times.

Several antioxidants were screened using HPDSC. Oil AL-11848, which is one of the better candidate oils to date, was supplemented with various commercially available high-temperature antioxidants, with the effects on HPDSC break time shown in Table 13. The best HPDSC performance was obtained by supplementing AL-11848 with 2 wt% each of p,p'-dioctyldiphenylamine and phenyl-α-naphthylamine which increased the break time from 267 to 575 minutes. Oil AL-11761 was supplemented with 2 wt% of p,p'-dioctyldiphenylamine, and virtually no improvement in HPDSC was observed.

Oil blends B and H (from Table 13) were evaluated in the high-temperature CLR-D engine test with the results discussed previously (Table 11). Despite the excellent improvement in HPDSC break time observed for Oil blend H, this formulation did not display improved oxidation resistance in CLR-D test No. A30. While HPDSC appears to correctly rank the CLR-D performance of oils which have not been supplemented with antioxidants, it may not be useful for predicting the engine performance of oils formulated with additional antioxidants.

Several oils which have been evaluated in the CLR-D were tested in a 48-hour 200°C oxidation-corrosion test (FTM 5308) to determine if this procedure can be used as a high-temperature diesel lubricant screening test. The results of the FTM 5308 test are presented in Table 14 and are compared with CLR-D test results. FTM 5308 at 200°C did not appear to consistently predict oil oxidation or bearing material attack in the CLR-D engine. Additional FTM 5308 tests will be run at a higher temperature to increase oxidation-corrosion severity.

TABLE 12. HPDSC RESULTS

AL No.	Oil Description	HPDSC Time to Break, min	CLR-D Test No.	CLR-D Test Hr	CLR-D Reasons for Stopping
10690	Polyalkylated benzene	10	A17	16	BC, wear
8980	Petroleum	37	A11	33.5	OT
11788	Petroleum	41	A21	21	OT
11663	Petroleum	42	A14	19	OT, BC
11874	PAO-6cS	50	A28	40	RB
8924	PAO/polyolester	52	A10	17	BC
11877	Petroleum	61	A22	40.5	OT
11662	80% PAO/20% petroleum	65	A19	26	BC
11873	PAO-4cS	78	Not Tested		
11683	PAO	81	A13	30.5	BC, OT, RS
11507	Polyolester	89	A7	17	BC
11878	Diphenylether	91	A27	49	C
11661	PAO	97	A12	8.5	BC
11876	Diester	111	A29	40	C
11761	Diester	123	A16	48	OT
11723	PAO	137	A15	21	BC
11875	Polyolester (TMP)	143	A23	42	RS
11848	Diester/PAO	267	A20	45	OT
8925	Diester	297	A1	49	C

BC = Bearing corrosion
OT = Oil thickening
RS = Ring sticking
C = Completed test
RB = Ring Broke

TABLE 13. HPDSC TESTS -- SUPPLEMENTAL ANTIOXIDANTS

	A	B	C	D	E	F	G	H
Oils								
AL-11848	---	---	100	100	100	100	100	100
AL-11761	100	100	---	---	---	---	---	---
Supplemental Antioxidants, wt% Added								
p,p'-dioctyldiphenylamine	---	2	---	2	---	---	1	2
phenyl-α-naphthylamine	---	---	---	---	2	---	1	2
Phenothiazine	---	---	---	---	---	2	---	---
HPDSC								
Break Time in Minutes	123	128	267	372	432	326	414	575

IV. CONCLUSIONS

Lubricant performance at high cylinder wall temperatures was defined using an uncooled single-cylinder diesel engine operated at conditions which simulate the Cummins Minimum-Cooled Diesel Engine. The following lubricant-related problems were observed:

- Lubricant oxidation--oil too thick to pump; corrosive products formed and bearings attacked.
- Lubricant volatility--high oil consumption, oil thickening.
- Engine deposits--ring sticking.

A variety of high-temperature candidate lubricants was evaluated in the uncooled single-cylinder diesel engine. Two promising lubricants have been identified:

TABLE 14. HIGH-TEMPERATURE OIL PERFORMANCE IN FTM 5308

		Oxidation-Corrosion Test, 392°F/48 Hr					CLR-D Test						
					Wt Loss							Used Oil, PPM	
Oil Code	Oil Description	Test No.	Δ Neut. No.	K Vis 40°C % Inc.	Cu, mg/cm^2	Pb, mg/cm^2	Test No.	Test Hr	Δ TAN	K Vis 100°C Inc, cSt	Oxid. by IR	Cu	Pb
AL-8925	Diester	2A	+0.5	+40	0.6	215.5	A1	49	+0.2	+26.9	0.08	12	40
AL-8924	Polyolester/ PAO	1A	+2.1	-14	2.9	69.0	A10	17	+6	+4.6	ND*	136	391
AL-8980	Petroleum	1B	+1.1	+120	4.5	30.7	A11	33.5	+4.5	+79	0.57	21	<60
AL-11507	Polyolester	3B	+3.4	+44	4.0	47.7	A7 A8	17 13	+4.9 +6.3	-0.6 +5.6	ND ND	175 50	710 684
AL-11683	PAO	5A	+1.3	+17	4.3	36.4	A13	30.5	+9.6	solid	1.24	97	345
AL-11661	PAO	3A	+1.2	+35	9.0	67.3	A12	8.5	+2.5	+15.2	0.61	171	361
AL-11663	Petroleum	4A 2B	+1.8 +1.5	+104 +105	4.1 2.6	13.3 6.2	A14	19	+8.1	+89.5	0.73	39	187
AL-11723	PAO	6A	+1.5	+120	9.4	138.9	A15	21	+8.2	+38.7	1.0	216	588

*ND = Not determined

- AL-11878 which contains diphenylether basestock material and a calcium detergent-dispersant additive system.
- AL-11848 which contains diester and PAO basestocks and a barium detergent-dispersant additive system; AL-11848 does not contain zinc.

While these two oils had the best overall high-temperature performance of the candidates tested, they were still deficient in oxidation stability/oil thickening properties.

High-pressure differential scanning calorimetry (HPDSC) and FTM5308 were investigated for use as high-temperature lubricant bench screening methods. Neither method was completely satisfactory, and additional development of a bench oxidation screening technique is needed.

V. RECOMMENDATIONS

The following recommendations for additional effort are offered:

- Improved high-temperature lubricants need to be developed which have better resistance to oxidation, produce less engine deposits, and exhibit lower oil consumption rates.
- High-temperature lubricant investigations should include tests using an engine with keystone-type rings, because this ring configuration is used in the minimum-cooled engine by Cummins.
- Bench-scale screening methodologies need to be developed which will predict oxidation resistance and friction/wear characteristics of high-temperature lubricants.
- The program should be expanded to include lubrication aspects of ceramic components and the compatibility of high-temperature lubricants with ceramic materials.
- Specification requirements should be developed for an engine oil to be used in high-temperature, minimum-cooled/adiabatic diesel engines.

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APPENDIX A

PROPERTIES OF TEST LUBRICANTS

AL-7135-L

Desc: Syn Diesel Lubricant

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	67.35
2	K Vis @ 100°C, cSt	D 445	9.95
3	VI	D 2270	143
12	Pour Point, °C	D 97	-34
13	Flash Point, °C	D 92	227
14	API, °	D 287	18.4
15	C Res, wt%	D 524	1.12
16	Sulfated Ash, wt%	D 874	1.02
17	TAN	D 664	2.45
18	TBN	D 664	7.87
18	TBN	D 664	6.78
20	Insols C5 A, wt%	D 893	.03
22	Insols C5 B, wt%	D 893	.01
26	Ba, wt%	XRF	<.01
28	Ca, wt%	XRF	.08
28	Ca, wt%	XRF	.09
29	Ca, wt%	AA	.11
31	Mg, wt%	AA	.078
31	Mg, wt%	AA	.096
32	Zn, wt%	XRF	.13
32	Zn, wt%	XRF	.12
33	Zn, wt%	AA	.13
34	P, wt%	XRF	.11
34	P, wt%	XRF	.10
36	S, wt%	XRF	.34
38	N, wt%	CLM	.21
41	Na, wt%	AA	0.0
44	Cl, wt%	AA	<.01
45	IR No.	---	1337
50	GC BPD @ 1 wt% OFF, °C	AFLRL	349
51	GC BPD @ 5 wt% OFF, °C	AFLRL	418
52	GC BPD @ 10 wt% OFF, °C	AFLRL	445
53	GC BPD @ 20 wt% OFF, °C	AFLRL	536
54	GC BPD @ 30 wt% OFF, °C	AFLRL	549
55	GC BPD @ 40 wt% OFF, °C	AFLRL	566
56	GC BPD @ 50 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	56.8

AL-8924-L
Desc: Engine Oil, Synthetic

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	56.0
2	K Vis @ 100°C, cSt	D 445	10.0
3	VI	D 2270	167
11	BPT, °C	D 3829	-32
13	Flash Point, °C	D 92	224
15	C Res, wt%	D 524	1.1
16	Sulfated Ash, wt%	D 874	1.1
17	TAN	D 664	3.0
19	TBN	D 2896	6.3
27	Ba, wt%	AA	<0.005
29	Ca, wt%	AA	0.25
31	Mg, wt%	AA	<0.001
32	Zn, wt%	XRF	.13
33	Zn, wt%	AA	0.12/0.13
34	P, wt%	XRF	0.13
36	S, wt%	XRF	0.33
38	N, wt%	CLM	0.14
46	Evap @ 191°C, wt% loss	D 972	7
50	GC BPD @ 1 wt% OFF, °C	AFLRL	335
51	GC BPD @ 5 wt% OFF, °C	AFLRL	389
52	GC BPD @ 10 wt% OFF, °C	AFLRL	406
53	GC BPD @ 20 wt% OFF, °C	AFLRL	418
54	GC BPD @ 30 wt% OFF, °C	AFLRL	431
55	GC BPD @ 40 wt% OFF, °C	AFLRL	436
56	GC BPD @ 50 wt% OFF, °C	AFLRL	451
57	GC BPD @ 60 wt% OFF, °C	AFLRL	465
58	GC BPD @ 70 wt% OFF, °C	AFLRL	472
59	GC BPD @ 80 wt% OFF, °C	AFLRL	481
60	GC BPD @ 90 wt% OFF, °C	AFLRL	508
61	End Point, °C	AFLRL	593
62	Residue, wt%	AFLRL	0.0

AL-8925-L
Desc: Oil, Engine, Arctic

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	26.32
2	K Vis @ 100°C, cSt	D 445	5.90
3	VI	D 2270	179
4	CCS Vis @ -18°C, cp	D 2602	525
12	Pour Point, °C	D 97	-64
13	Flash Point, °C	D 92	234
14	API, °	D 287	21.2
15	C Res, wt%	D 524	1.42
16	Sulfated Ash, wt%	D 874	1.45
17	TAN	D 664	0.24
18	TBN	D 664	7.59
27	Ba, wt%	AA	0.905
29	Ca, wt%	AA	<0.0005
31	Mg, wt%	AA	<0.0001
32	Zn, wt%	XRF	0.0
34	P, wt%	XRF	0.0
36	S, wt%	XRF	0.02
38	N, wt%	CLM	0.0986
50	GC BPD @ 1 wt% OFF, °C	AFLRL	362
51	GC BPD @ 5 wt% OFF, °C	AFLRL	434
52	GC BPD @ 10 wt% OFF, °C	AFLRL	451
53	GC BPD @ 20 wt% OFF, °C	AFLRL	457
54	GC BPD @ 30 wt% OFF, °C	AFLRL	461
55	GC BPD @ 40 wt% OFF, °C	AFLRL	465
56	GC BPD @ 50 wt% OFF, °C	AFLRL	472
57	GC BPD @ 60 wt% OFF, °C	AFLRL	486
58	GC BPD @ 70 wt% OFF, °C	AFLRL	515
59	GC BPD @ 80 wt% OFF, °C	AFLRL	581
60	GC BPD @ 90 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	20

AL-8980-L
Desc: Oil, Engine, OE/HDO-30

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	109.11
2	K Vis @ 100°C, cSt	D 445	11.65
3	VI	D 2270	93
13	Flash Point, °C	D 92	223
14	API, °	D 287	25.2
15	C Res, wt%	D 524	2.1
16	Sulfated Ash, wt%	D 874	1.78
17	TAN	D 664	2.3
19	TBN	D 2896	13.9
28	Ca, wt%	XRF	.57
29	Ca, wt%	AA	0.48
31	Mg, wt%	AA	0.0018
32	Zn, wt%	XRF	.08
34	P, wt%	XRF	.07
36	S, wt%	XRF	0.65
45	IR No.	---	1832
46	Evap @ 191°C, wt% loss	D 972	8
50	GC BPD @ 1 wt% OFF, °C	AFLRL	326
51	GC BPD @ 5 wt% OFF, °C	AFLRL	336
52	GC BPD @ 10 wt% OFF, °C	AFLRL	387
53	GC BPD @ 20 wt% OFF, °C	AFLRL	415
54	GC BPD @ 30 wt% OFF, °C	AFLRL	437
55	GC BPD @ 40 wt% OFF, °C	AFLRL	456
56	GC BPD @ 50 wt% OFF, °C	AFLRL	477
57	GC BPD @ 60 wt% OFF, °C	AFLRL	505
58	GC BPD @ 70 wt% OFF, °C	AFLRL	547
59	GC BPD @ 80 wt% OFF, °C	AFLRL	>600
60	GC BPD @ 90 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	25.0

AL-10690-L
Desc: Oil, Engine, Arctic

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	30.32
2	K Vis @ 100°C, cSt	D 445	6.10
3	VI	D 2270	154
13	Flash Point, °C	D 92	221
14	API, °	D 287	29.0
16	Sulfated Ash, wt%	D 874	.93
17	TAN	D 664	3.31
18	TBN	D 664	6.43
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.17
31	Mg, wt%	AA	.041
32	Zn, wt%	XRF	.09
33	Zn, wt%	AA	.12
34	P, wt%	XRF	.07
36	S, wt%	XRF	.25
38	N, wt%	CLM	.033
45	IR No.	---	2465
50	GC BPD @ 1 wt% OFF, °C	AFLRL	351
51	GC BPD @ 5 wt% OFF, °C	AFLRL	405
52	GC BPD @ 10 wt% OFF, °C	AFLRL	410
53	GC BPD @ 20 wt% OFF, °C	AFLRL	414
54	GC BPD @ 30 wt% OFF, °C	AFLRL	418
55	GC BPD @ 40 wt% OFF, °C	AFLRL	423
56	GC BPD @ 50 wt% OFF, °C	AFLRL	427
57	GC BPD @ 60 wt% OFF, °C	AFLRL	433
58	GC BPD @ 70 wt% OFF, °C	AFLRL	439
59	GC BPD @ 80 wt% OFF, °C	AFLRL	448
60	GC BPD @ 90 wt% OFF, °C	AFLRL	463
61	End Point, °C	AFLRL	584
62	Residue, wt%	AFLRL	0.0

AL-11132-L
Desc: Oil, Exp. Diesel, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	66.86
2	K Vis @ 100°C, cSt	D 445	10.52
3	VI	D 2270	148
13	Flash Point, °C	D 92	290
16	Sulfated Ash, wt%	D 874	.04
17	TAN	D 664	.71
18	TBN	D 664	0.0
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	0.0
32	Zn, wt%	XRF	0.0
34	P, wt%	XRF	.13
36	S, wt%	XRF	0.0
45	IR No.	---	2196
48	Evap. @ 260°C, wt% Loss	D 972	2.1
50	GC BPD @ 1 wt% OFF, °C	AFLRL	275
51	GC BPD @ 5 wt% OFF, °C	AFLRL	315
52	GC BPD @ 10 wt% OFF, °C	AFLRL	334
53	GC BPD @ 20 wt% OFF, °C	AFLRL	353
54	GC BPD @ 30 wt% OFF, °C	AFLRL	367
55	GC BPD @ 40 wt% OFF, °C	AFLRL	379
56	GC BPD @ 50 wt% OFF, °C	AFLRL	391
57	GC BPD @ 60 wt% OFF, °C	AFLRL	402
58	GC BPD @ 70 wt% OFF, °C	AFLRL	416
59	GC BPD @ 80 wt% OFF, °C	AFLRL	432
60	GC BPD @ 90 wt% OFF, °C	AFLRL	456
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	1.5

AL-11147-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	182.82
2	K Vis @ 100°C, cSt	D 445	19.48
3	Vi	D 2270	122
13	Flash Point, °C	D 92	258
16	Sulfated Ash, wt%	D 874	3.2
17	TAN	D 664	4.6
18	TBN	D 664	13.5
28	Ca, wt%	XRF	.95
29	Ca, wt%	AA	1.06
31	Mg, wt%	AA	.001
32	Zn, wt%	XRF	.08
34	P, wt%	XRF	.06
36	S, wt%	XRF	.75
45	IR No.	---	2197
48	Evap. @ 260°C, wt% Loss	D 972	2.6
50	GC BPD @ 1 wt% OFF, °C	AFLRL	365
51	GC BPD @ 5 wt% OFF, °C	AFLRL	433
52	GC BPD @ 10 wt% OFF, °C	AFLRL	473
53	GC BPD @ 20 wt% OFF, °C	AFLRL	501
54	GC BPD @ 30 wt% OFF, °C	AFLRL	524
55	GC BPD @ 40 wt% OFF, °C	AFLRL	544
56	GC BPD @ 50 wt% OFF, °C	AFLRL	564
57	GC BPD @ 60 wt% OFF, °C	AFLRL	600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	37.6

AL-11386-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	157.57
2	K Vis @ 100°C, cSt	D 445	19.72
3	VI	D 2270	144
13	Flash Point, °C	D 92	240
16	Sulfated Ash, wt%	D 874	1.14
17	TAN	D 664	1.62
18	TBN	D 664	7.37
26	Ba, wt%	XRF	<.01
28	Ca, wt%	XRF	.23
31	Mg, wt%	AA	.002
32	Zn, wt%	XRF	.15
34	P, wt%	XRF	.09
36	S, wt%	XRF	.45
38	N, wt%	CLM	.024
45	IR No.	---	2292
50	GC BPD @ 1 wt% OFF, °C	AFLRL	339
51	GC BPD @ 5 wt% OFF, °C	AFLRL	411
52	GC BPD @ 10 wt% OFF, °C	AFLRL	429
53	GC BPD @ 20 wt% OFF, °C	AFLRL	438
54	GC BPD @ 30 wt% OFF, °C	AFLRL	471
55	GC BPD @ 40 wt% OFF, °C	AFLRL	517
56	GC BPD @ 50 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	57.2

AL-11507-L
Desc: HTL, Engine, Oil,

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	61.87
2	K Vis @ 100°C, cSt	D 445	9.62
3	VI	D 2270	138
7	CCS Vis @ -15°C, cp	D 2602	2100
8	CCS Vis @ -20°C, cp	D 2602	3900
12	Pour Point, °C	D 97	-31
13	Flash Point, °C	D 92	263
14	API, °	D 287	18.5
15	C Res, wt%	D 524	.77
16	Sulfated Ash, wt%	D 874	.75
17	TAN	D 664	2.34
18	TBN	D 664	7.37
20	Insols C5 A, wt%	D 893	.01
21	Insols Tol A, wt%	D 893	0.00
21	Insols Tol A, wt%	D 893	.01
22	Insols C5 B, wt%	D 893	.01
23	Insols Tol B, wt%	D 893	0.0
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.05
31	Mg, wt%	AA	.09
32	Zn, wt%	XRF	.09
34	P, wt%	XRF	.06
36	S, wt%	XRF	.27
38	N, wt%	CLM	.091
44	CL, wt%	AA	<.01
45	IR No.	---	2325
46	Evap @ 191°C, wt% loss	D 972	10.5
50	GC BPD @ 1 wt% OFF, °C	AFLRL	351
51	GC BPD @ 5 wt% OFF, °C	AFLRL	402
52	GC BPD @ 10 wt% OFF, °C	AFLRL	443
53	GC BPD @ 20 wt% OFF, °C	AFLRL	474
54	GC BPD @ 30 wt% OFF, °C	AFLRL	475
55	GC BPD @ 40 wt% OFF, °C	AFLRL	476
56	GC BPD @ 50 wt% OFF, °C	AFLRL	478
57	GC BPD @ 60 wt% OFF, °C	AFLRL	481
58	GC BPD @ 70 wt% OFF, °C	AFLRL	539
59	GC BPD @ 80 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	29.4

AL-11511-L
Desc: Oil, Experimental, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	43.37
2	K Vis @ 100°C, cSt	D 445	8.41
3	VI	D 2270	174
13	Flash Point, °C	D 92	266
16	Sulfated Ash, wt%	D 874	.28
17	TAN	D 664	0.00
18	TBN	D 664	2.14
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	<.05
31	Mg, wt%	AA	<.0001
32	Zn, wt%	XRF	0.0
34	P, wt%	XRF	.09
36	S, wt%	XRF	.03
38	N, wt%	CLM	.029
44	Cl, wt%	AA	.02
45	IR No.	---	2329
46	Evap @ 191°C, wt% loss	D 972	8.9
50	GC BPD @ 1 wt% OFF, °C	AFLRL	402
51	GC BPD @ 5 wt% OFF, °C	AFLRL	457
52	GC BPD @ 10 wt% OFF, °C	AFLRL	472
53	GC BPD @ 20 wt% OFF, °C	AFLRL	475
54	GC BPD @ 30 wt% OFF, °C	AFLRL	475
55	GC BPD @ 40 wt% OFF, °C	AFLRL	476
56	GC BPD @ 50 wt% OFF, °C	AFLRL	476
57	GC BPD @ 60 wt% OFF, °C	AFLRL	477
58	GC BPD @ 70 wt% OFF, °C	AFLRL	479
59	GC BPD @ 80 wt% OFF, °C	AFLRL	481
60	GC BPD @ 90 wt% OFF, °C	AFLRL	496
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	7.9

AL-11661-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	79.42
2	K Vis @ 100°C, cSt	D 445	11.55
3	VI	D 2270	138
13	Flash Point, °C	D 92	239
16	Sulfated Ash, wt%	D 874	.78
17	TAN	D 664	3.05
18	TBN	D 664	5.51
26	Ba, wt%	XRF	0.0
29	Ca, wt%	AA	0.09
31	Mg, wt%	AA	0.043
32	Zn, wt%	XRF	.15
34	P, wt%	XRF	.09
36	S, wt%	XRF	.30
38	N, wt%	CLM	.099
45	IR No.	---	2430
50	GC BPD @ 1 wt% OFF, °C	AFLRL	357
51	GC BPD @ 5 wt% OFF, °C	AFLRL	404
52	GC BPD @ 10 wt% OFF, °C	AFLRL	408
53	GC BPD @ 20 wt% OFF, °C	AFLRL	417
54	GC BPD @ 30 wt% OFF, °C	AFLRL	429
55	GC BPD @ 40 wt% OFF, °C	AFLRL	474
56	GC BPD @ 50 wt% OFF, °C	AFLRL	498
57	GC BPD @ 60 wt% OFF, °C	AFLRL	568
58	GC BPD @ 70 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	38.8

AL-11662-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	85.71
2	K Vis @ 100°C, cSt	D 445	11.50
3	VI	D 2270	124
13	Flash Point, °C	D 92	242
14	API, °	D 287	32.7
16	Sulfated Ash, wt%	D 874	.74
17	TAN	D 664	3.05
18	TBN	D 664	5.58
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.09
31	Mg, wt%	AA	.038
32	Zn, wt%	XRF	.13
34	P, wt%	XRF	.09
36	S, wt%	XRF	.53
38	N, wt%	CLM	.106
45	IR No.	---	2528
50	GC BPD @ 1 wt% OFF, °C	AFLRL	283
51	GC BPD @ 5 wt% OFF, °C	AFLRL	321
52	GC BPD @ 10 wt% OFF, °C	AFLRL	339
53	GC BPD @ 20 wt% OFF, °C	AFLRL	358
54	GC BPD @ 30 wt% OFF, °C	AFLRL	370
55	GC BPD @ 40 wt% OFF, °C	AFLRL	382
56	GC BPD @ 50 wt% OFF, °C	AFLRL	393
57	GC BPD @ 60 wt% OFF, °C	AFLRL	404
58	GC BPD @ 70 wt% OFF, °C	AFLRL	417
59	GC BPD @ 80 wt% OFF, °C	AFLRL	432
60	GC BPD @ 90 wt% OFF, °C	AFLRL	453
61	End Point, °C	AFLRL	515
62	Residue, wt%	AFLRL	0.0

AL-11663-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	98.22
2	K Vis @ 100°C, cSt	D 445	11.29
3	VI	D 2270	101
13	Flash Point, °C	D 92	227
16	Sulfated Ash, wt%	D 874	.84
17	TAN	D 664	2.48
18	TBN	D 664	7.47
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.09
31	Mg, wt%	AA	.04
32	Zn, wt%	XRF	.11
34	P, wt%	XRF	.06
36	S, wt%	XRF	1.11
38	N, wt%	CLM	.107
45	IR No.	---	2438
50	GC BPD @ 1 wt% OFF, °C	AFLRL	353
51	GC BPD @ 5 wt% OFF, °C	AFLRL	400
52	GC BPD @ 10 wt% OFF, °C	AFLRL	414
53	GC BPD @ 20 wt% OFF, °C	AFLRL	431
54	GC BPD @ 30 wt% OFF, °C	AFLRL	446
55	GC BPD @ 40 wt% OFF, °C	AFLRL	460
56	GC BPD @ 50 wt% OFF, °C	AFLRL	475
57	GC BPD @ 60 wt% OFF, °C	AFLRL	495
58	GC BPD @ 70 wt% OFF, °C	AFLRL	548
59	GC BPD @ 80 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	26.1

AL-11683-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	119.75
2	K Vis @ 100°C, cSt	D 445	15.28
3	VI	D 2270	133
13	Flash Point, °C	D 92	247
16	Sulfated Ash, wt%	D 874	1.91
17	TAN	D 664	2.58
18	TBN	D 664	12.78
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.40
31	Mg, wt%	AA	.003
32	Zn, wt%	XRF	.08
34	P, wt%	XRF	.07
36	S, wt%	XRF	.47
38	N, wt%	CLM	.032
45	IR No.	---	2431
50	GC BPD @ 1 wt% OFF, °C	AFLRL	377
51	GC BPD @ 5 wt% OFF, °C	AFLRL	416
52	GC BPD @ 10 wt% OFF, °C	AFLRL	423
53	GC BPD @ 20 wt% OFF, °C	AFLRL	461
54	GC BPD @ 30 wt% OFF, °C	AFLRL	471
55	GC BPD @ 40 wt% OFF, °C	AFLRL	480
56	GC BPD @ 50 wt% OFF, °C	AFLRL	509
57	GC BPD @ 60 wt% OFF, °C	AFLRL	599
58	GC BPD @ 70 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	39

AL-11723-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	76.75
2	K Vis @ 100°C, cSt	D 445	11.42
3	VI	D 2270	140
13	Flash Point, °C	D 92	251
16	Sulfated Ash, wt%	D 874	.99
17	TAN	D 664	2.98
18	TBN	D 664	6.98
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.15
31	Mg, wt%	AA	.04
32	Zn, wt%	XRF	.14
34	P, wt%	XRF	.09
36	S, wt%	XRF	.34
38	N, wt%	CLM	.109
44	Cl, wt%	AA	.03
45	IR No.	---	2454
50	GC BPD @ 1 wt% OFF, °C	AFLRL	365
51	GC BPD @ 5 wt% OFF, °C	AFLRL	413
52	GC BPD @ 10 wt% OFF, °C	AFLRL	420
53	GC BPD @ 20 wt% OFF, °C	AFLRL	437
54	GC BPD @ 30 wt% OFF, °C	AFLRL	476
55	GC BPD @ 40 wt% OFF, °C	AFLRL	490
56	GC BPD @ 50 wt% OFF, °C	AFLRL	522
57	GC BPD @ 60 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	40.5

AL-11761-L
Desc: Oil, Engine, HTL, Synthetic

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	63.31
2	K Vis @ 100°C, cSt	D 445	10.73
3	VI	D 2270	161
13	Flash Point, °C	D 92	221
16	Sulfated Ash, wt%	D 874	1.96
17	TAN	D 664	3.81
18	TBN	D 664	13.22
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.46
31	Mg, wt%	AA	.0014
32	Zn, wt%	XRF	.10
34	P, wt%	XRF	.09
36	S, wt%	XRF	.57
38	N, wt%	CLM	.061
45	IR No.	---	2459
50	GC BPD @ 1 wt% OFF, °C	AFLRL	245
51	GC BPD @ 5 wt% OFF, °C	AFLRL	375
52	GC BPD @ 10 wt% OFF, °C	AFLRL	406
53	GC BPD @ 20 wt% OFF, °C	AFLRL	422
54	GC BPD @ 30 wt% OFF, °C	AFLRL	436
55	GC BPD @ 40 wt% OFF, °C	AFLRL	452
56	GC BPD @ 50 wt% OFF, °C	AFLRL	459
57	GC BPD @ 60 wt% OFF, °C	AFLRL	467
58	GC BPD @ 70 wt% OFF, °C	AFLRL	473
59	GC BPD @ 80 wt% OFF, °C	AFLRL	482
60	GC BPD @ 90 wt% OFF, °C	AFLRL	506
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	<0.1

AL-11788-L
Desc: Engine Oil, Mineral, 15W-40

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	110.02
2	K Vis @ 100°C, cSt	D 445	14.59
3	VI	D 2270	136
13	Flash Point, °C	D 92	221
14	API, °	D 287	28.5
16	Sulfated Ash, wt%	D 874	1.14
17	TAN	D 664	3.0
18	TBN	D 664	5.7
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.07
31	Mg, wt%	AA	.125
32	Zn, wt%	XRF	.12
33	Zn, wt%	AA	.15
34	P, wt%	XRF	.14
36	S, wt%	XRF	.64
38	N, wt%	CLM	.097
45	IR No.	---	2480
50	GC BPD @ 1 wt% OFF, °C	AFLRL	338
51	GC BPD @ 5 wt% OFF, °C	AFLRL	376
52	GC BPD @ 10 wt% OFF, °C	AFLRL	388
53	GC BPD @ 20 wt% OFF, °C	AFLRL	403
54	GC BPD @ 30 wt% OFF, °C	AFLRL	416
55	GC BPD @ 40 wt% OFF, °C	AFLRL	429
56	GC BPD @ 50 wt% OFF, °C	AFLRL	442
57	GC BPD @ 60 wt% OFF, °C	AFLRL	459
58	GC BPD @ 70 wt% OFF, °C	AFLRL	484
59	GC BPD @ 80 wt% OFF, °C	AFLRL	544
60	GC BPD @ 90 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	18.5

AL-11848-L

Desc: Engine/Transmission Lube, SAE 50

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	133.29
2	K Vis @ 100°C, cSt	D 445	17.81
3	VI	D 2270	148
13	Flash Point, °C	D 92	227
14	API, °	D 287	22.8
16	Sulfated Ash, wt%	D 874	2.38
17	TAN	D 664	1.62
18	TAN	D 664	10.62
26	Ba, wt%	XRF	1.48
28	Ca, wt%	XRF	<.01
31	Mg, wt%	AA	<.001
32	Zn, wt%	XRF	<.01
33	Zn, wt%	AA	<.01
34	P, wt%	XRF	.09
36	S, wt%	XRF	.12
45	IR No.	---	2573
50	GC BPD @ 1 wt% OFF, °C	AFLRL	308
51	GC BPD @ 5 wt% OFF, °C	AFLRL	368
52	GC BPD @ 10 wt% OFF, °C	AFLRL	407
53	GC BPD @ 20 wt% OFF, °C	AFLRL	437
54	GC BPD @ 30 wt% OFF, °C	AFLRL	446
55	GC BPD @ 40 wt% OFF, °C	AFLRL	451
56	GC BPD @ 50 wt% OFF, °C	AFLRL	459
57	GC BPD @ 60 wt% OFF, °C	AFLRL	471
58	GC BPD @ 70 wt% OFF, °C	AFLRL	497
59	GC BPD @ 80 wt% OFF, °C	AFLRL	>600
60	GC BPD @ 90 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	21.4

AL-11874-L
Desc: Engine Oil, PAO, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	47.36
2	K Vis @ 100°C, cSt	D 445	7.73
3	VI	D 2270	131
13	Flash Point, °C	D 92	229
16	Sulfated Ash, wt%	D 874	1.67
17	TAN	D 664	3.9
18	TBN	D 664	13.2
28	Ca, wt%	XRF	.53
32	Zn, wt%	XRF	.11
34	P, wt%	XRF	.13
36	S, wt%	XRF	.57
38	N, wt%	CLM	.04
45	IR No.	---	2712
50	GC BPD @ 1 wt% OFF, °C	AFLRL	355
51	GC BPD @ 5 wt% OFF, °C	AFLRL	407
52	GC BPD @ 10 wt% OFF, °C	AFLRL	414
53	GC BPD @ 20 wt% OFF, °C	AFLRL	424
54	GC BPD @ 30 wt% OFF, °C	AFLRL	443
55	GC BPD @ 40 wt% OFF, °C	AFLRL	463
56	GC BPD @ 50 wt% OFF, °C	AFLRL	469
57	GC BPD @ 60 wt% OFF, °C	AFLRL	476
58	GC BPD @ 70 wt% OFF, °C	AFLRL	486
59	GC BPD @ 80 wt% OFF, °C	AFLRL	512
60	GC BPD @ 90 wt% OFF, °C	AFLRL	552
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	6.3

AL-11875-L
Desc: Engine Oil, TMP, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	21.81
2	K Vis @ 100°C, cSt	D 445	4.84
3	VI	D 2270	150
13	Flash Point, °C	D 92	232
14	API, °	D 287	14.7
16	Sulfated Ash, wt%	D 874	1.72
17	TAN	D 664	3.55
18	TBN	D 664	11.87
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.34
31	Mg, wt%	AA	<.001
32	Zn, wt%	XRF	.07
33	Zn, wt%	AA	.11
34	P, wt%	XRF	.06
36	S, wt%	XRF	.37
50	GC BPD @ 1 wt% OFF, °C	AFLRL	331
51	GC BPD @ 5 wt% OFF, °C	AFLRL	401
52	GC BPD @ 10 wt% OFF, °C	AFLRL	421
53	GC BPD @ 20 wt% OFF, °C	AFLRL	423
54	GC BPD @ 30 wt% OFF, °C	AFLRL	424
55	GC BPD @ 40 wt% OFF, °C	AFLRL	427
56	GC BPD @ 50 wt% OFF, °C	AFLRL	429
57	GC BPD @ 60 wt% OFF, °C	AFLRL	432
58	GC BPD @ 70 wt% OFF, °C	AFLRL	435
59	GC BPD @ 80 wt% OFF, °C	AFLRL	440
60	GC BPD @ 90 wt% OFF, °C	AFLRL	448
61	End Point, °C	AFLRL	576
62	Residue, wt%	AFLRL	0.0

AL-11876-L
Desc: Engine Oil, Diester, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	17.18
2	K Vis @ 100°C, cSt	D 445	4.24
3	VI	D 2270	161
13	Flash Point, °C	D 92	221
16	Sulfated Ash, wt%	D 874	1.82
17	TAN	D 664	3.6
18	TBN	D 664	12.7
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.44
29	Ca, wt%	AA	.49
31	Mg, wt%	AA	<.001
32	Zn, wt%	XRF	.09
33	Zn, wt%	AA	.11
34	P, wt%	XRF	.08
36	S, wt%	XRF	.41
38	N, wt%	CLM	.04
45	IR No.	---	2743
50	GC BPD @ 1 wt% OFF, °C	AFLRL	338
51	GC BPD @ 5 wt% OFF, °C	AFLRL	386
52	GC BPD @ 10 wt% OFF, °C	AFLRL	398
53	GC BPD @ 20 wt% OFF, °C	AFLRL	402
54	GC BPD @ 30 wt% OFF, °C	AFLRL	404
55	GC BPD @ 40 wt% OFF, °C	AFLRL	407
56	GC BPD @ 50 wt% OFF, °C	AFLRL	410
57	GC BPD @ 60 wt% OFF, °C	AFLRL	414
58	GC BPD @ 70 wt% OFF, °C	AFLRL	419
59	GC BPD @ 80 wt% OFF, °C	AFLRL	428
60	GC BPD @ 90 wt% OFF, °C	AFLRL	460
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	5.4

AL-11877-L
Desc: Engine Oil, Mineral, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	50.08
2	K Vis @ 100°C, cSt	D 445	7.25
3	VI	D 2270	104
13	Flash Point, °C	D 92	222
14	API, °	D 287	27.4
16	Sulfated Ash, wt%	D 874	1.88
17	TAN	D 664	3.6
18	TBN	D 664	13.2
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.46
31	Mg, wt%	AA	.0014
32	Zn, wt%	XRF	.10
33	Zn, wt%	AA	.12
34	P, wt%	XRF	.07
36	S, wt%	XRF	.60
45	IR No.	---	2586
50	GC BPD @ 1 wt% OFF, °C	AFLRL	331
51	GC BPD @ 5 wt% OFF, °C	AFLRL	363
52	GC BPD @ 10 wt% OFF, °C	AFLRL	378
53	GC BPD @ 20 wt% OFF, °C	AFLRL	396
54	GC BPD @ 30 wt% OFF, °C	AFLRL	412
55	GC BPD @ 40 wt% OFF, °C	AFLRL	425
56	GC BPD @ 50 wt% OFF, °C	AFLRL	438
57	GC BPD @ 60 wt% OFF, °C	AFLRL	452
58	GC BPD @ 70 wt% OFF, °C	AFLRL	470
59	GC BPD @ 80 wt% OFF, °C	AFLRL	497
60	GC BPD @ 90 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	12.1

AL-11878-L
Desc: Engine Oil, Alkyldiphenylether, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	81.83
2	K Vis @ 100°C, cSt	D 445	9.29
3	VI	D 2270	87
13	Flash Point, °C	D 92	232
16	Sulfated Ash, wt%	D 874	1.83
17	TAN	D 664	3.80
18	TBN	D 664	13.60
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.49
29	Ca, wt%	AA	.49
31	Mg, wt%	AA	<.001
32	Zn, wt%	XRF	.11
33	Zn, wt%	AA	.11
34	P, wt%	XRF	.11
36	S, wt%	XRF	.47
38	N, wt%	CLM	.03
45	IR No.	---	2701
50	GC BPD @ 1 wt% OFF, °C	AFLRL	360
51	GC BPD @ 5 wt% OFF, °C	AFLRL	415
52	GC BPD @ 10 wt% OFF, °C	AFLRL	438
53	GC BPD @ 20 wt% OFF, °C	AFLRL	446
54	GC BPD @ 30 wt% OFF, °C	AFLRL	451
55	GC BPD @ 40 wt% OFF, °C	AFLRL	455
56	GC BPD @ 50 wt% OFF, °C	AFLRL	460
57	GC BPD @ 60 wt% OFF, °C	AFLRL	466
58	GC BPD @ 70 wt% OFF, °C	AFLRL	475
59	GC BPD @ 80 wt% OFF, °C	AFLRL	514
60	GC BPD @ 90 wt% OFF, °C	AFLRL	580
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	7.9

AL-11953-L
Desc: Oil, Engine, HTL

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	122.98
2	K Vis @ 100°C, cSt	D 445	12.38
3	VI	D 2270	90
13	Flash Point, °C	D 92	240
16	Sulfated Ash, wt%	D 874	.89
17	TAN	D 664	3.05
18	TBN	D 664	6.41
26	Ba, wt%	XRF	0.0
28	Ca, wt%	XRF	.17
31	Mg, wt%	AA	<.001
32	Zn, wt%	XRF	.10
33	Zn, wt%	AA	.13
34	P, wt%	XRF	.09
36	S, wt%	XRF	.38
38	N, wt%	CLM	.025
45	IR No.	---	2263

AL-12289-L
Desc: Oil, Engine, REO-203

Test Code	Test Description	Test Method	Result
1	K Vis @ 40°C, cSt	D 445	102.60
2	K Vis @ 100°C, cSt	D 445	11.55
3	VI	D 2270	100
13	Flash Point, °C	D 92	249
16	Sulfated Ash, wt%	D 874	.99
17	TAN	D 664	2.8
18	TBN	D 664	4.4
22	Insols C5 B, wt%	D 893	<.01
23	Insols Tol B, wt%	D 893	<.01
26	Ba, wt%	XRF	<.01
28	Ca, wt%	XRF	.27
31	Mg, wt%	AA	<.005
32	Zn, wt%	XRF	.12
33	Zn, wt%	AA	.10
34	P, wt%	XRF	.10
36	S, wt%	XRF	.48
38	N, wt%	CLM	.015
45	IR No.	---	2906
50	GC BPD @ 1 wt% OFF, °C	AFLRL	347
51	GC BPD @ 5 wt% OFF, °C	AFLRL	403
52	GC BPD @ 10 wt% OFF, °C	AFLRL	427
53	GC BPD @ 20 wt% OFF, °C	AFLRL	447
54	GC BPD @ 30 wt% OFF, °C	AFLRL	459
55	GC BPD @ 40 wt% OFF, °C	AFLRL	470
56	GC BPD @ 50 wt% OFF, °C	AFLRL	481
57	GC BPD @ 60 wt% OFF, °C	AFLRL	496
58	GC BPD @ 70 wt% OFF, °C	AFLRL	518
59	GC BPD @ 80 wt% OFF, °C	AFLRL	>600
60	GC BPD @ 90 wt% OFF, °C	AFLRL	>600
61	End Point, °C	AFLRL	>600
62	Residue, wt%	AFLRL	24.4

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